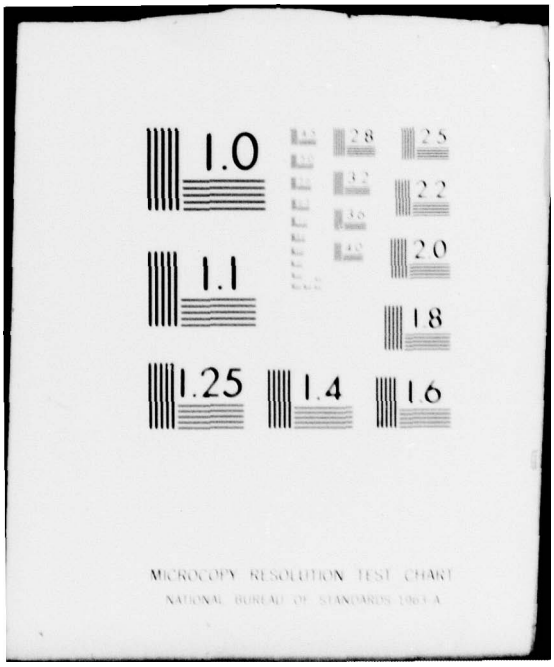
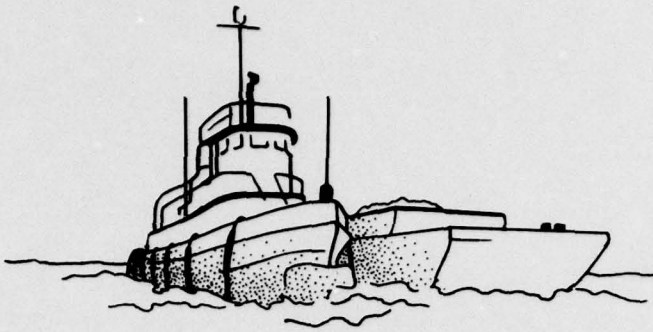
AD-A073 267 WISCONSIN UNIV-MADISON MARINE STUDIES CENTER F/G 13/2
AN ASSESSMENT OF THE ENVIRONMENTAL EFFECTS OF DREDGED MATERIAL --ETC(U)
MAR 76 J P KEILLOR, J YOUNG, R A RAGOTZKIE DACW37-74-C-0013
UNCLASSIFIED NL

1 OF 2
AD A073267


1.0
1.1
1.25
1.4
1.6
2.8
3.2
3.6
4.0
2.5
2.2
2.0
1.8
MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963-A

AD A073267



LEVEL III

FINAL REPORT

AN ASSESSMENT OF THE ENVIRONMENTAL EFFECTS OF DREDGED MATERIAL DISPOSAL IN LAKE SUPERIOR

DDC
RECEIVED
AUG 29 1979
A

DDC FILE COPY

Volume 4

Dynamics of Mixing and Dispersal

By

J. Philip Keillor, John Young, and Robert A. Ragotzkie

MARINE STUDIES CENTER
UNIVERSITY OF WISCONSIN, MADISON

March, 1976

DISTRIBUTION STATEMENT A
Approved for public release;
Distribution Unlimited

79 08 29 047

(9) FINAL REPORT,

(6) AN ASSESSMENT OF THE ENVIRONMENTAL EFFECTS
OF
DREDGED MATERIAL DISPOSAL
IN
LAKE SUPERIOR .

A REPORT TO THE U.S. ARMY CORPS OF ENGINEERS
FROM THE MARINE STUDIES CENTER

Volume 4 .

DYNAMICS OF MIXING AND DISPERSAL .

By

(10) J. Philip Keillor, John Young, and Robert A. Ragotzkie

MARINE STUDIES CENTER
INSTITUTE FOR ENVIRONMENTAL STUDIES
UNIVERSITY OF WISCONSIN-MADISON
1225 W. DAYTON STREET
MADISON, WISCONSIN 53706

(11) Mar 76

(12) 113p.

DISTRIBUTION STATEMENT A
Approved for public release;
Distribution Unlimited

(15) This research was supported by the U.S. Army Corps of Engineers, St. Paul District under Contract Number DACW37-74-C-0013.

79 08 29 047
411 355 LD

TABLE OF CONTENTS

	PAGE
Authors	iv
List of Figures	v
List of Tables	vii
Conclusions	viii
I. Introduction	1
A. Sediment Transport	8
B. Study Description	11
C. Methods of Analysis for the Keweenaw Study	12
II. The Climate of the Lake Superior Basin	
A. Summary Description of the Area	14
B. Lake Temperatures	14
C. Precipitation and Evaporation	17
D. Winds	18
E. Waves	23
F. Weather Systems	25
III. Dynamics of Coastal Waters: Keweenaw North Entry	
A. Summary Description of Physical Processes	28
B. Winds	30
C. Coastal Currents	30
D. Changes in Water Temperatures and Currents	35
1. Description of events	
a. June 2-21, 1974	35
b. June 22-July 12, 1974	38
c. July 13-31, 1974	41
2. Current direction	43
3. Current speed	43
4. Predicted dispersal of fine dredged material	44
5. Periodic fluctuations in water velocity and temperature	45
E. Wave Action	48
F. Conclusions	55
IV. Dynamics of the Keweenaw Waterway	
A. Summary Description	56
B. Water Level Fluctuations	57
1. North Entry	59
2. Houghton	59
3. South Entry	59
4. Phase and coherence between stations	60

PAGE

C. Water Temperature Fluctuations 61
D. Channel Flow
1. Direction 63
2. Speed 66
3. Estimate of volumetric transport 66
4. Channel flow fluctuations 67

V. Dynamics of Offshore Waters: Duluth-Superior Area 69
A. Summary of Water Transport Processes 69
B. Winds 71
C. Currents 73
1. Region 1 - North Shore area 81
2. Region 2 - Minnesota Point area 81
3. Region 3 - Dutchman's Creek area 84
4. Region 4 86
5. Region 5 - Amnicon River area 88
D. Thermal Stratification and Upwelling 88
E. Wave Action 93
F. Turbidity 97
G. Conclusions 98
VI. Bibliography 99

Accession For
NTIS GRA&I
DDC TAB
Unannounced
Justification
By
Distribution/
Availability Codes
Dist. Avail and/or special
A-1

THE AUTHORS

This report was prepared by Philip Keillor, John Young and Robert Ragotzkie. Philip Keillor is the program manager for the interdisciplinary research project which included this study. He has a Master's degree in Ocean Engineering. John Young is a research assistant and a graduate student in Physical Oceanography. Robert Ragotzkie directed the interdisciplinary project. He is Professor of Meteorology and Environmental Studies, Director of the Marine Studies Center and Director of the University of Wisconsin Sea Grant College Program.

LIST OF FIGURES

FIGURE		PAGE
1.	ERTS Satellite Photo of the Keweenaw Peninsula -- June 25, 1974	2
2.	ERTS Satellite Photo of the Duluth-Superior Area -- August 12, 1972	3
3.	Keweenaw Waterway	6
4.	Duluth-Superior Harbor -- Offshore Dump Sites	7
5.	Wind Speed and Direction, Synthesized Lake Winds -- Lake Superior -- January-April, 1957-1966	20
6.	Wind Speed and Direction, Synthesized Lake Winds -- Lake Superior -- May-August, 1957-1966	21
7.	Wind Speed and Direction, Synthesized Lake Winds -- Lake Superior -- September-December, 1957-1966	22
8.	Frequency Distribution of Current Direction near the Upper Entry, Keweenaw Waterway -- June 2-August 1, 1974	32
9.	Frequency Distribution of the Northeast Current Speed near the Upper Entry, Keweenaw Waterway -- June 2-August 1, 1974	33
10.	Frequency Distribution of the Southwest Current Speed near the Upper Entry, Keweenaw Waterway -- June 2-August 1, 1974	34
11.	Nearshore Currents and Water Temperature in the Vicinity of the Upper Entry, Keweenaw Waterway -- June 2-21, 1974	37
12.	Nearshore Currents and Water Temperature in the Vicinity of the Upper Entry, Keweenaw Waterway -- June 22-July 12, 1974	40
13.	Nearshore Currents and Water Temperature in the Vicinity of the Upper Entry, Keweenaw Waterway -- July 13-31, 1974	42
14.	Depth of Influence for Waves at the Upper Entry, Keweenaw-Peninsula	52
15.	Nearshore Turbidity and Waterway Outflow -- Keweenaw Upper Entry -- June 11, 1974	64

FIGURE		PAGE
16.	Dredge GAILLARD Operating in the Keweenaw Upper Entry During a Period of Waterway Outflow -- June 11, 1974	65
17.	Bathymetric Map of the Duluth-Superior Area.	70
18.	Wind Speed and Direction -- Duluth, Minnesota -- May-August, 1951-1960	74
19.	Wind Speed and Direction -- Duluth, Minnesota -- September-December, 1951-1960	75
20.	Wind Speed and Direction -- Duluth, Minnesota -- January-April, 1951-1960	76
21.	Annual Wind Speed, Frequency and Direction -- Duluth, Minnesota -- 1951-1960	77
22.	Surface Transport Pattern for Winds from the NW -- October 6, 1972	78
23.	Surface Transport Pattern for Winds from the West -- July 3, 1973	79
24.	Surface Transport Path for Winds from the E and SE -- September 30, 1973	80
25.	Distribution of Currents near the North Shore -- Region 1 -- Vicinity of the Lester River	82
26.	Distribution of Currents off Minnesota Point -- Region 2	83
27.	Distribution of Currents off Dutchman's Creek -- Region 3	85
28.	Current Distribution -- Region 4	87
29.	Seasonal Temperature Profiles Near Duluth-Superior	90
30.	Influence of Wind on Thermal Stratification	91
31.	Cross Sectional Diagram of an Upwelling Event -- Duluth, Minnesota, May 26, 1975	92
32.	Fetch Limited Deep Water Wave Characteristics for ENE Winds -- Duluth-Superior	94

LIST OF TABLES

TABLES		PAGE
1.	Climatological Data for the Lake Superior Basin	16
2.	Locations of Cyclonic and Anti-Cyclonic Systems near the Keweenaw Peninsula -- Primary and Secondary Tracks	27
3.	Fundamental Periods of Nearshore Water Velocity and Temperature Fluctuations	47
4.	Effective Fetch at the Keweenaw Waterway-North Entry and at Eagle Harbor	49
5.	Wave Data for the Eagle Harbor Area of Lake Superior -- May 19-December 4, 1966	51
6.	Wave Characteristics for Three Storm Events at the Keweenaw Waterway-Upper Entry	54
7.	Periodic Water Level Fluctuations	58
8.	Phase Angles and Phase Coherence for Three Stations Along the Keweenaw Waterway	61
9.	Estimate of Keweenaw Waterway Average Flow Rate	67
10.	Dominant Periods of Channel Current Fluctuations	68
11.	Estimated Wave Characteristics at Duluth-Superior for Three Northeast Spring Storms in 1974.	96

Conclusions

A. Keweenaw North Entry

1. The coastal current near the North Entry flows primarily towards the northeast during the summer months at speeds which sometimes reach 50 cm/sec. Northeasterly currents can be expected during periods of light wind and when westerly winds are blowing.

2. Sometimes the coastal current flows toward the southwest during the summer with observed maximum speeds of 45-50 cm/sec. Southwesterly current flow usually occurs when the winds are blowing from an easterly direction.

3. If in-lake spoil disposal occurs offshore when the coastal current is flowing towards the northeast, the suspended fine sediment may be transported as far as 20 km/day. Less advection of suspended spoil is likely to occur during periods of southwesterly current flow or during periods of varying flow direction.

4. Dispersal of spoil dumped in the lake can be reduced by scheduling disposal operations before nearshore thermal stratification develops in July and August. Thermal stratification inhibits the settling of fine sediment.

5. Placement of dredge spoil in depths of 24 m or less will probably result in dispersal of most of the material by wave and current action. Spoil deposited at depths approaching 40 m will be subject to disturbance by occasional storm waves. Spoil dumped in 95 m depths or greater is not likely to be disturbed by storm waves.

6. The direction of flow in the Waterway was primarily towards the south during the summers of 1974 and 1975. Northward flow of channel water through the North Entry and into Lake Superior can be expected when easterly winds are blowing and when a high pressure system is located north of the Keweenaw Peninsula. Southward flow of Lake Superior water into the North Entry can be expected when westerly winds are blowing and when a low pressure system is located north of the Peninsula.

7. Waterway flow velocities are primarily affected by water level changes. Water level changes occur over intervals of less than one hour to several days.

8. Fluctuations in channel water level are due to changes in lake wind direction and speed, lake seiches and channel seiches. Over a 12 hour period, water levels varied as much as 50 cm at the North Entry, 10 cm at Houghton and 71 cm at the South Entry.

B. Duluth-Superior Area

1. Placement of dredge spoil in depths of 18 m or less will probably result in dispersal of the fine material in the spoil deposits by wave and current action. Fine dredge spoil dumped in 40 m depths will be subject to some occasional re-suspension by storm waves. Deposits of spoil at depths greater than 60 m are not likely to be disturbed by wave action except during rare storms with sustained winds of more than 50 mph velocity.

2. Dispersal of suspended spoil can be reduced during dumping by scheduling in-lake disposal operations to occur prior to mid-June when

the thermocline begins to develop or in November when the lake is cooling toward an isothermal condition.

3. Lake water in the Duluth-Superior area moves in complex circulation patterns which are influenced by wind direction, degree of thermal stratification and the physical features of the basin. Dispersal of suspended dredge spoil and the characteristics of natural turbidity are probably different for each potential in-lake disposal area.

I. Introduction

The two areas selected for study, the north coast of the Keweenaw Peninsula and the western embayment of Lake Superior near Duluth-Superior, differ greatly in their mixing and dispersal characteristics. Nearshore turbidity along the Keweenaw Peninsula ~~(Figure 1)~~ contrasts to relatively large turbid eddies off of Duluth-Superior ~~(Figure 2)~~. Turbidity along the north coast of the Keweenaw Peninsula is frequently confined to an even narrower coastal area later in the summer which is under the influence of the strong, well-defined coastal current.

Flowing northeast along the north shore of the Keweenaw Peninsula during the summer months, the Keweenaw current follows the coast at speeds ranging from 40 to 90 cm/sec. (Yeske, 1973). Although sometimes narrower, the Keweenaw current normally ranges in width from five to ten kilometers. The surface thermal structure of this current indicates the presence of eddies, meanders, and counter-currents (Ragotzkie, 1966; Smith, 1972). Other studies of the Keweenaw Current structure include Ragotzkie and Bratnik (1965), Smith and Ragotzkie (1970) and Yeske, et al. (1972).

 (Figure 1)

Figure 1 ERTS Satellite Phot of the Keweenaw Peninsula--June 25, 1974

Figure 2 ERTS Satellite Photo of Duluth-Superior Area--August 12, 1972

In recent years, the dredging and spoil disposal activities of the Corps of Engineers at the Keweenaw Waterway have centered in the North[1] Entry and in the Lily Pond (Figure 3). Dredging in the Entry creates a small turbid plume which disperses into or out of the North Entry, depending on the direction of Keweenaw Waterway flow. In-lake dispersal of suspended sediments from dredging or spoil dumping is determined by lake currents and by small scale diffusion processes. Dredge spoil from the most frequently dredged area, the North Entry, has been classified as unpolluted by the Environmental Protection Agency (EPA), and declared suitable for in-lake disposal. Consequently, the Corps of Engineers have dumped dredge spoil from this area either offshore in 18m depths of water or nearshore in 4m depths of water as beach nourishment for McLain State Park.

The processes governing sediment dispersal in the western tip of Lake Superior appear to be more complex than sediment dispersal processes along the Keweenaw Peninsula. Located at the western tip of Lake Superior, Duluth-Superior harbor receives the flow of two rivers, the Nemadji and the St. Louis, which discharge into Lake Superior through two man-made ship canals. When the suspended sediment carried by each river reaches the lake, it is dispersed by wind-driven lake currents, eddies, and small scale diffusion processes. Consequently, the lake water in this region is frequently turbid.

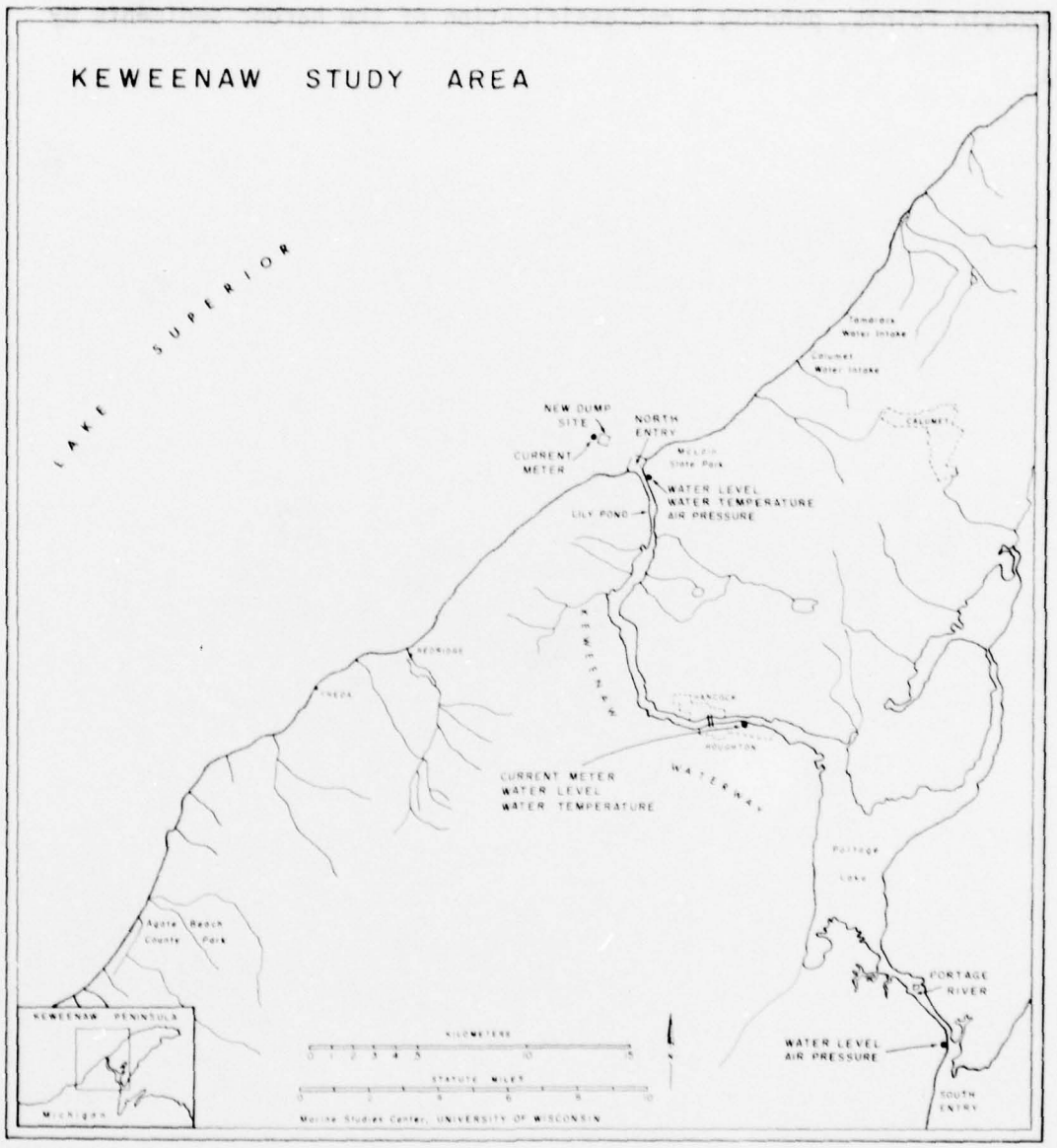
At Duluth-Superior, considerable amounts of dredge material had been dumped in the lake, prior to 1968, at one of two disposal areas (Figure 4). Subsequent disposal of spoil was shifted to the 21st Avenue Slip as

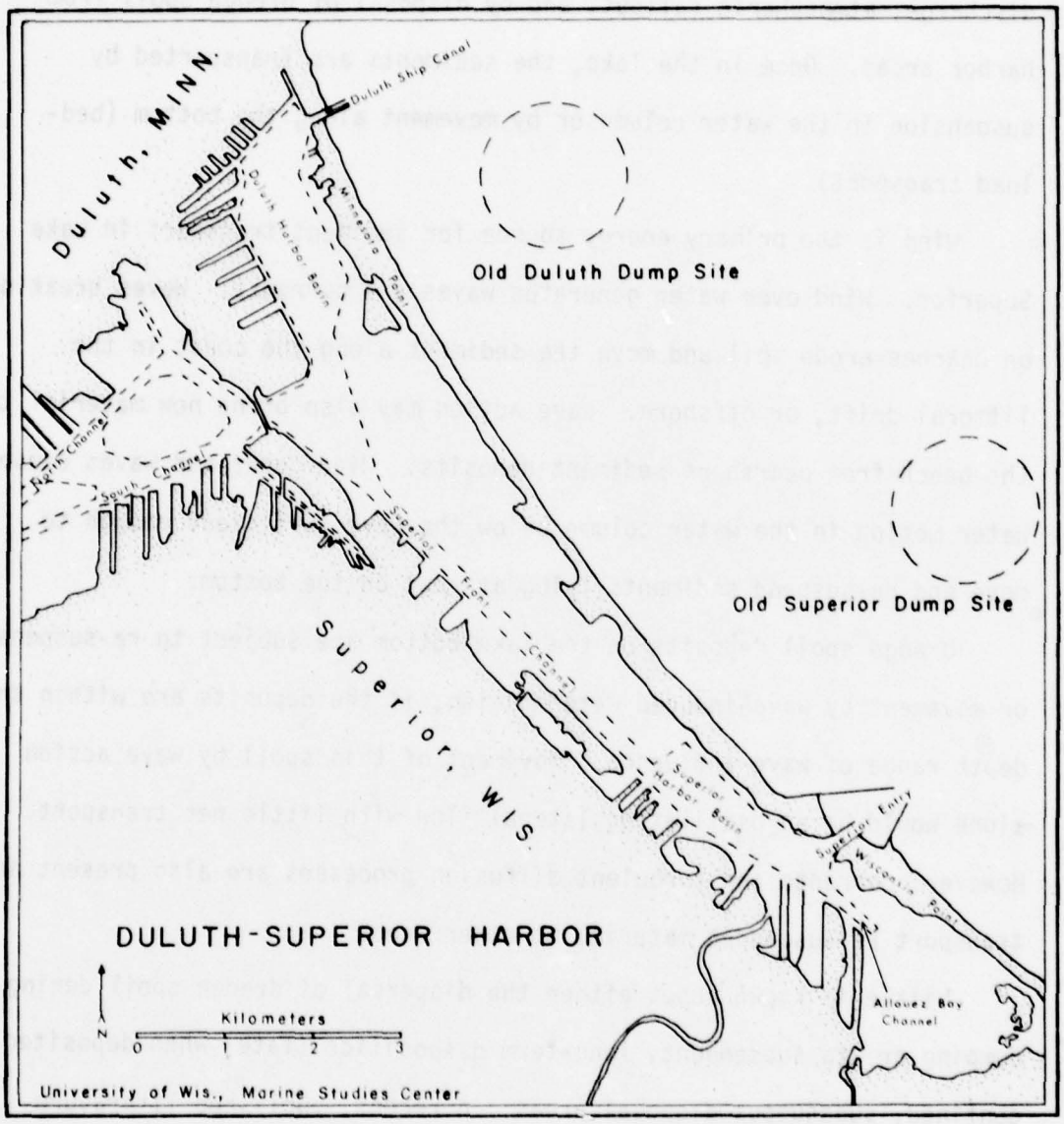
---

[1]Also referred to as the Upper Entry.

a result of the harbor being declared polluted by the EPA. In 1975, in-lake spoil disposal resumed with beach nourishment of Minnesota and Wisconsin Points, pending a reclassification of the harbor sediments by EPA.

6 (Figure 3)


KEWEENAW STUDY AREA
LAKE SUPERIOR
NEW DUMP SITE
NORTH ENTRY
CURRENT METER
WATER LEVEL
WATER TEMPERATURE
AIR PRESSURE
LILY POND
Tamarack Water Intake
Calumet Water Intake
CALUMET
HOUGHTON
CURRENT METER
WATER LEVEL
WATER TEMPERATURE
KEWEENAW WATERWAY
Portage Lake
PORTAGE RIVER
WATER LEVEL
AIR PRESSURE
SOUTH ENTRY
KEWEENAW PENINSULA
Michigan
KILOMETERS
STATUTE MILES
Marine Studies Center, UNIVERSITY OF WISCONSIN


Duluth, MINN.
Duluth Ship Canal
Minnesota Point
Duluth Harbor Basin
Old Duluth Dump Site
Old Superior Dump Site
Superior Entry
South Channel
Superior, WIS.
Superior Harbor Basin
Superior Entry
Wisconsin Point
Allouez Bay Channel
DULUTH-SUPERIOR HARBOR
N
Kilometers
0 1 2 3
University of Wis., Marine Studies Center

A. Sediment Transport

Sediments may enter the lake by wave erosion of beaches, river discharge, atmospheric fallout, and by disposal of dredge spoil from harbor areas. Once in the lake, the sediments are transported by suspension in the water column or by movement along the bottom (bed-load transport).

Wind is the primary energy source for sediment transport in Lake Superior. Wind over water generates waves and currents. Waves breaking on beaches erode soil and move the sediment along the coast in the littoral drift, or offshore. Wave action may also bring new material to the beach from nearshore sediment deposits. Wind-generated waves cause water motion in the water column below the wave sufficient enough to move and re-suspend sediments lying at rest on the bottom.

Dredge spoil deposits on the lake bottom are subject to re-suspension or movement by wave-induced water motion, if the deposits are within the depth range of wave influence. Movement of this spoil by wave action alone would be an oscillating lateral flow with little net transport. However, currents and turbulent diffusion processes are also present and transport re-suspended material to other areas.

Little is known about either the dispersal of dredge spoil during dumping or its subsequent, long-term disposition (fate) when deposited in un-confined, subaqueous disposal areas. A recent, published literature review indicates that there are no adequate mathematical models capable of tracing spoil movement in an estuarine or large lake environment from the time of release until deposition on the bottom (Johnson, 1973). The most significant mathematical model that Johnson found was one

developed for predicting dispersion and settling of wastes barged into the ocean for disposal (Koh and Chang, 1973). This model provides a useful conceptual picture of disposal dynamics.

Koh and Chang trace spoil disposal in three steps: convective descent, dynamic collapse, and long term diffusion. When the spoil is dumped from a barge, it descends toward the bottom by momentum, buoyancy, and gravitational forces. During the descent, water is entrained in the spoil "cloud", and the larger particles and consolidated masses settle out of the cloud at higher velocities. If the ambient conditions in the water column are uniform (no stratification), the spoil cloud undergoes dynamic collapse when it reaches the bottom: spreading horizontally with additional water entrainment.

If stratified ambient conditions exist in the water column, the descending spoil cloud may or may not reach the bottom, depending on the strength of the density gradient. If the descending cloud encounters a strongly stratified layer (such as a strong thermocline), the cloud may undergo initial dynamic collapse with horizontal spreading and entrainment of water. The mass of fine sediment and water may reach a neutrally buoyant position in the water column where net vertical movement ceases and some oscillation occurs as the cloud approaches hydrostatic equilibrium. While the cloud is suspended in the stratified layer, it may expand and drift away from the disposal area due to turbulence and currents. If the stratification is not very strong, the spoil descends from the surface with some dynamic collapse occurring in the stratified layer and at the bottom. During the descent and dynamic collapse there may be some advection of the spoil cloud away from the dump site due to currents.

Assessment of factors controlling the long term fate of spoil deposited in unconfined, subaqueous disposal sites was the subject of a recent literature study (Basco et al., 1974). Among their conclusions were the following:

1. Analytical methods do not exist which permit the computation of quantities and rates of spread of finite volumes of dredged material in a flow field.

2. Knowledge of incipient sediment motion is of restricted value since quantities and rates are of direct interest to determine material spread.

3. Previous field experiments failed to adequately monitor the environment during the test, hence were of little value to draw conclusions or generalizations.

Recent laboratory work by Krishnappan (1975) indicates that granular material, dumped in deep water, has a motion which can be described in two phases: the initial entrainment phase, and a final settling phase. The settling phase may not occur in most Great Lakes disposal operations since the depth of water must be great enough for the velocities of the individual particles to reach their terminal velocity. Krishnappan identifies the governing parameters for the motion of the granular particles and the easily computed characteristics of the resulting spoil mound in terms of diameter and depth. Koh and Chang's assumption of descending dredged material as a fluid within the fluid of the water column indicates that their more complex model is better suited for fine sediments such as silts and clays. The analytical results of Krishnappan, and Koh and Chang are idealized models, useful for describing the dynamics of disposal for either granular or fine sediments. They do not include the frequently encountered conditions of heterogeneous material and clumping.

Subsequent sections of this report present information on the physical processes of mixing and dispersal at Duluth-Superior and the Keweenaw Waterway North Entry areas. The data on waves can be used to provide a rough estimate of re-suspension possibilities for various dump site locations. The data on currents provides a picture of potential advection at certain locations during spoil disposal. Since thermal stratification enhances dispersal during dumping, information on the seasonal development of lake stratification can be used to assess effects of disposal at different times of the year.

B. Study Description

Our investigation of the mixing and dispersal processes in the Duluth-Superior area is based on the research of Michael Sydor (1974), who used ERTS imagery and in situ current measurements, and on published wind and other climatological data. We also took depth measurements for a bathymetric map of the area: Figure 17.

At the Keweenaw North Entry, our research focused on two subjects: (1) currents and related physical processes in the lake, and (2) the Keweenaw Waterway flow.

Lake currents and water temperature were recorded at 10 m depth on an Aanderaa RCM-4 current meter anchored 1.5 km from the North Entry (bearing 289^{o} from the North Entry Light) in 18 m of water. This location was on the western edge of the new experimental dump site. Supplemental offshore data consisted of aerial photographic flights used to record varying conditions of nearshore turbidity and waterway flow.

In the Keweenaw Waterway (Figure 3), data was gathered at three locations: (1) near the North Entry--water level, air pressure and water temperature were recorded on instruments at the Portage Coast Guard Station; (2) close to the Waterway's midpoint--water level, water temperature, channel current speed and direction were recorded at the Michigan Technological University (MTU) dock in Houghton; and (3) near the South Entry--water level and air pressure were recorded at Rasce's Marina.

C. Methods of Analysis for the Keweenaw Study

The Aanderaa current meter system adds the revolutions of a rotor which is spun by the current and records the total revolutions at ten minute intervals on magnetic tape. The instantaneous current direction and water temperature are also recorded at the same ten minute intervals. We had the magnetic tape data processed and punched on computer cards. These data were plotted against time to find major changes in current speed and direction and water temperature for comparison with the passage of atmospheric pressure systems and changes in wind direction.

Channel currents, water temperature and water level data were digitized at 2.5 minute intervals and then transferred to computer cards. Water level data were averaged over various intervals.[1]

Water level fluctuations at the three stations were analyzed for periodicity and compared with one another. Periodic fluctuations were examined through the use of spectral analysis. Spectral analysis is a method of time series analysis where a long data record in the time

[1] 5, 10, 40 minutes, 1, 2, 4, 12, 24 hour intervals.

domain is converted into a concise form in the frequency domain. It is a statistical procedure which determines the frequency distribution of the energy (variance) of a time series over a defined frequency range. Peaks in particular frequency bands indicate higher contents of energy in those bands than in neighboring ones. The higher the peak is, the stronger the periodic fluctuation is--indicating its relative importance or dominance as a physical phenomenon.

Cross spectral analysis of two simultaneous recorded time series provided information on the relationships between the two parameters. The coherence of various spectral frequency bands and the phase angle difference between them was determined for any two stations through the use of a modified spectral analysis program (Fee, 1969). Coherence ranges from zero to 1.00, and is analogous to the correlation coefficient of classical statistics. A coherence value near 1.00 for a specific frequency of two time series indicates that for this frequency the two series correlate exactly. Conversely, a coherence value near zero indicates no correlation between the two series at that frequency. The phase angle between frequency bands of high energy found at two locations was determined. The phase angle is measured in degrees and indicates the angular lead or lag of one series over another series. A positive phase angle means that series one leads series two. A negative phase angle means that series two leads series one.

II. The Climate of the Lake Superior Basin

A. Summary Description of the Area

Lake Superior with roughly 82,000 km^2 surface area is the largest freshwater lake in the world. Only Lake Baikal in Russia has a greater volume than Lake Superior, 12,200 cubic kilometers. This large, oligotrophic lake dominates the 210,000 km^2 lake basin, accounting for 39% of the basin area. Lake Superior modifies (and is influenced by) continental air from northwestern Canada, maritime polar air from the northern Pacific and occasionally maritime tropical air from the Gulf of Mexico. The settled weather of high pressure (anticyclonic) systems is normally interspersed every three to six days with low pressure (cyclonic) storm systems. The region experiences large variations in air temperature, humidity, and wind conditions due to the contrasting sources of air moving through the area. The lake, however, does not experience a similar wide range in temperature. The total seasonal variation in lake water temperature is less than 20^{o} C as compared to a land air temperature range of roughly 50^{o} C.

The climate of the Great Lakes Basin has been described by Phillips and McCulloch (1972). Much of the following information on the Lake Superior Basin is taken from their report.

B. Lake Temperatures

The data in Table 1 show the lake is warmest in August and September; it then gradually cools, reaching its lowest temperatures in February and March. At the Duluth airport, inland and somewhat removed from major lake influences, the highest air temperatures occur in July and

the lowest occur in January (Dicennial Census, 1963). The lake water lags behind the land air in warming and cooling by one to two months.

Ragotzkie and Niebauer (1975) give the following description of seasonal temperature changes in the water column near the coast:

> In early July Lake Superior is isothermal at near 4°C. Weak stratification begins in later July and August with warming extending to 46 meters. The maximum surface temperature, 14° C, and maximum stratification occur in September. Cooling begins in late September and continues throughout the fall until the entire water column reaches 4°C in early December. The entire lake continues to cool reaching a low temperature of nearly 2°C at the end of January. Winter stratification develops in February with the surface to 30 meter layer cooling to near 0°C. This very cold layer deepens throughout the winter reaching its maximum thickness in mid-April when 0°C water extends from the surface to 91 meters. The water at 152 meters and presumably deeper levels retains its low temperature of about 2°C.
>
> Surface warming begins in May and by June the lake is fully mixed vertically with a temperature of between 2 and 3°C. Warming of the entire water column continues until it reaches 4°C in July followed by surface warming and the onset of summer stratification.

They analyzed temperature data collected near Silver Bay, Minnesota from July, 1971 to July, 1972 at depths ranging from 152 m to the surface.

Off the northern coast of the Keweenaw Peninsula stratification begins to develop in July and is well established by early August (Smith, 1972). In a given year, the seasonal temperature patterns may differ from the above description due to climatic variations. Also, there are local variations depending upon proximity to the coast, depth of water and exposure to wind, waves, and currents. For example, near the Keweenaw North Entry, lake water temperatures reached 16°C. by June 21, 1974 at 10 m depths in 18 m of water, 1.5 km from the coast (page 35). In the shallow waters off Duluth-Superior, surface temperatures of 18°C. were recorded in July, 1974 (page 90).

Table 1. Some Climatological Data For The Lake Superior Basin

Month	Mean Precipitation (cm) Lake Basin[1]	Duluth[5]	Mean Surface Water Temperature[2] (^{0}C.)	Estimates of Lake Evaporation, Mean, Net Mass Transfer[3] (cm. of water)	Average Number of Days with Fog[4] Thunder Bay	Duluth	Marquette	Sault Ste. Marie
Jan.	4.65	2.82	1.7	11.7	1.3	3	1	2
Feb.	3.63	2.46	0	9.1	1.1	2	1	2
Mar.	4.22	4.09	0	5.8	1.8	3	1	3
Apr.	5.05	5.61	0.6	1.5	1.9	3	2	3
May	6.99	8.00	1.7	1.0	2.8	6	3	3
June	8.28	9.96	3.9	-3.6	5.0	7	4	4
July	8.05	9.32	6.7	-8.1	3.8	6	3	5
Aug.	8.03	8.86	11.7	-4.1	6.2	7	1	6
Sept.	8.76	8.18	11.7	3.3	5.3	6	1	7
Oct.	6.60	5.69	8.9	6.3	4.7	5	1	6
Nov.	6.17	4.17	6.1	10.4	2.5	3	1	3
Dec.	4.83	2.97	5.9	12.2	1.5	3	1	3
Annual	75.26	72.14	5.0	45.7	37.9	54	17	47

Sources 2-4: Data adapted from Phillips, D. W., McCulloch, J. A. W., The Climate of the Great Lakes Basin, Climatological Studies No. 20, Environment Canada, Toronto, 1972.

[1]Estimated by U.S. Corps of Engineers, Lake Survey District, for years 1900-1974.

[2]Calculated by Richards and Irbe, 1969, for years 1950-1968.

[3]Calculated by Richards and Irbe, 1969. Negative values indicate condensation. Period of estimate not given.

[4]Calculated for the years 1941-1960. Fog Days defined as days with visibility less than 5/8 miles for Canadian Station (Thunder Bay), 3/8 mile for U.S. stations.

[5]U.S. Department of Commerce, for years 1904 to 1973.

C. Precipitation and Evaporation

During the period of 1900-1974, the Lake Superior Basin received an average of 75.3 cm precipitation per year (Lake Survey Center, 1975). The last nine years of this span (1965 through 1973) had a higher precipitation rate of 79.4 cm per year. In the first nine months of 1973, precipitation was six percent above the long-term average, but during the same period in 1974, precipitation was the lowest since 1917 and reached a year-end total of only 60.5 cm (Great Lakes Commission, 1974).

Seasonal evaporation estimates for the lake are given in Table 1. The highest evaporation occurs from November through February. Annual amounts of evaporation from the Great Lakes are lowest for Lake Superior. In general, "evaporation is lowest in the spring when the lakes are cold relative to the air, and is greatest in the fall and early winter when the lakes are relatively warm." (Phillips & McCulloch, 1972).

D. Winds

Wind, exerting a surface shear stress on water, generates waves and currents. Associated with wave motion is a movement of surface water in the downwind direction (Stokes' drift). Through friction, the movement of surface water exerts a stress on underlying water, inducing a net flow at some angle to the right of the wind direction for water above the depth of wind influence (Ekman transport).

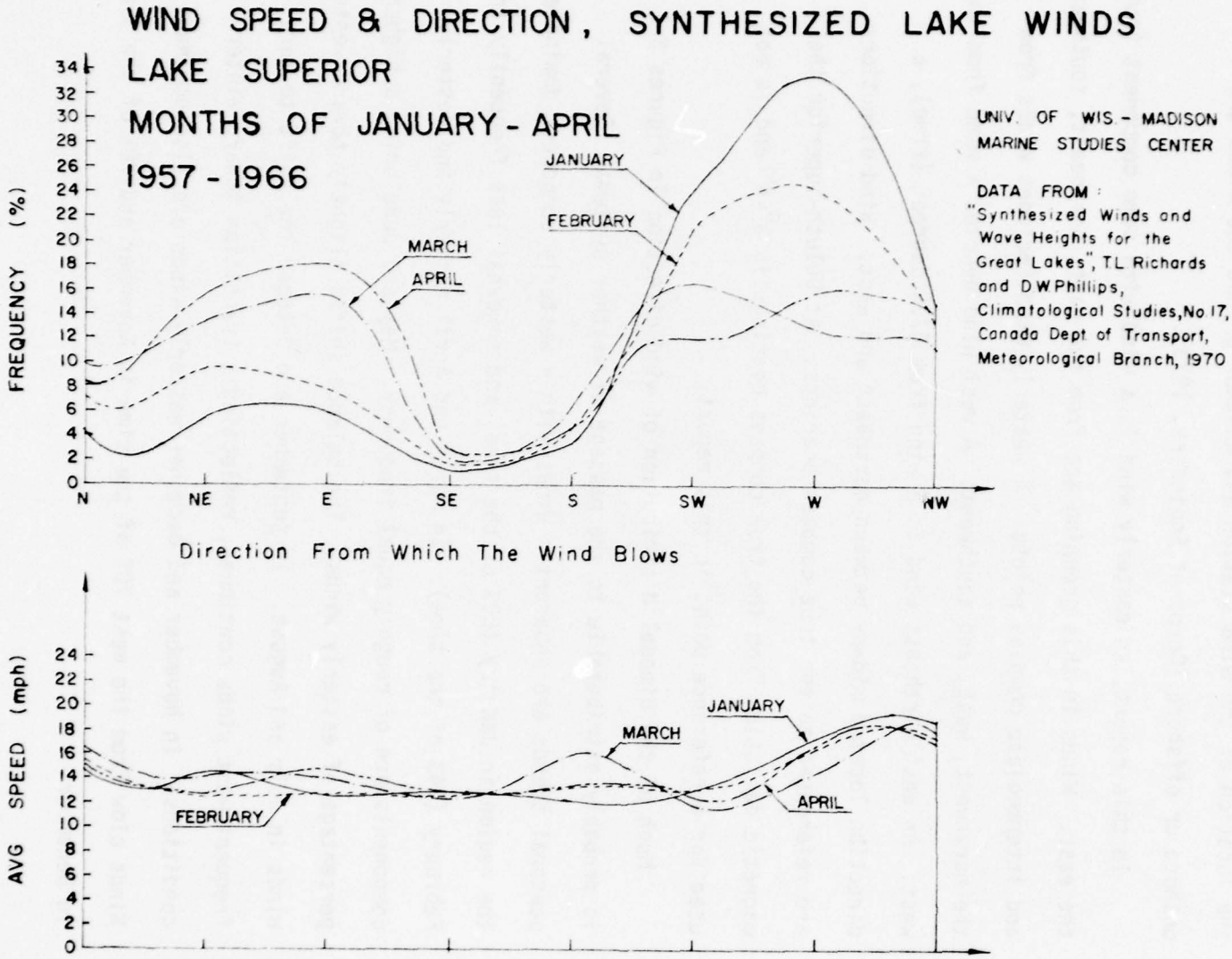
Continuous measurements of wind over water from a fixed location on Lake Superior are not available. Some wind data are available from ships traversing Lake Superior. However, these data consist of measurements made at various intervals from different locations in the shipping lanes. Wind data from shore stations are usually recorded at 1-3 hour intervals. Wave hindcasting and the correlation of water currents and water temperature changes with wind changes are severely limited by a lack of continuous over-lake wind measurements. In the absence of such data, wind measurements adapted from shore stations were used in this report.

Figures 5-7 give a rough idea of directional distributions and seasonal changes of winds in the western Lake Superior region. These curves are based on data from Thunder Bay, Ontario adjusted to approximate over-water wind speeds for the period of 1957-1966. Wind speed and direction reflect the passage of weather systems and the wind exposure peculiar to the recording site. There are differences in wind speed over land and water surfaces due to frictional differences and the thermal stability of the air mass near the water surface. The ratio of lake wind speeds to land wind speeds can vary from one to two (Richards and Phillips,

1970). The Corps of Engineers uses a ratio of 1.0 to 1.4 depending on the location of the wind station and whether or not the winds are onshore or offshore (Corps of Engineers, 1973).

In this report, an easterly wind is a wind with some component from the east. Winds in this grouping are from the east, northeast, southeast and intermediate compass points. A westerly wind includes winds from the northwest, west, and southwest. A west wind denotes a wind from the west. An east northeast wind is a wind from 67.5 degrees (true), a direction located midway between northeast and east. Wind directions are referenced to the true compass bearings. At Duluth-Superior the magnetic deviation from the true compass bearings in 3^{o}-4^{o} and is not used for a reference point in this report.

Much of the bimodel distribution of wind direction in Figures 5-7 is probably attributable to the passage of weather systems. Several seasonal trends are apparent. Winds with a westerly component dominate the region in January (80% of the time) and somewhat less frequently in February (74% of the time). In March and April easterly and westerly components are of roughly equal frequency. May and June bring a higher percentage of easterly winds. The balance shifts slightly toward westerly winds in July and August. In September and October the shift to more frequent west winds continues, reflecting a transition toward winter conditions. In November and December westerly winds are also dominant. Winds blow from the west 70% of the time in November and 78% of the time in December.

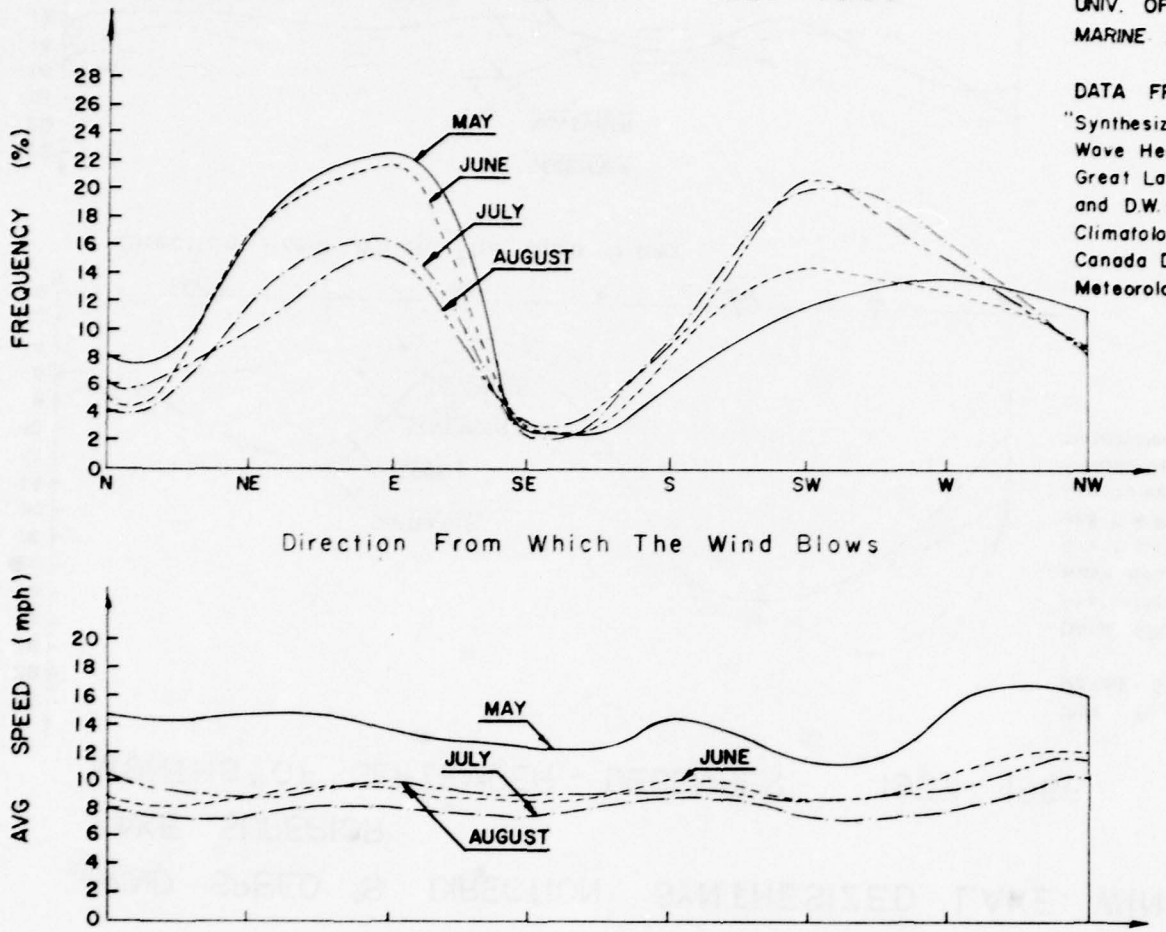

WIND SPEED & DIRECTION, SYNTHESIZED LAKE WINDS
LAKE SUPERIOR
MONTHS OF JANUARY - APRIL
1957 - 1966
FREQUENCY (%)
JANUARY
FEBRUARY
MARCH
APRIL
N
NE
E
SE
S
SW
W
NW
Direction From Which The Wind Blows
AVG SPEED (mph)
JANUARY
MARCH
APRIL
FEBRUARY
UNIV. OF WIS - MADISON
MARINE STUDIES CENTER
DATA FROM :
"Synthesized Winds and Wave Heights for the Great Lakes", T.L. Richards and D.W. Phillips, Climatological Studies, No 17, Canada Dept of Transport, Meteorological Branch, 1970

(Figure 5)

WIND SPEED & DIRECTION , SYNTHESIZED LAKE WINDS
LAKE SUPERIOR
MONTHS OF MAY - AUGUST 1957-1966

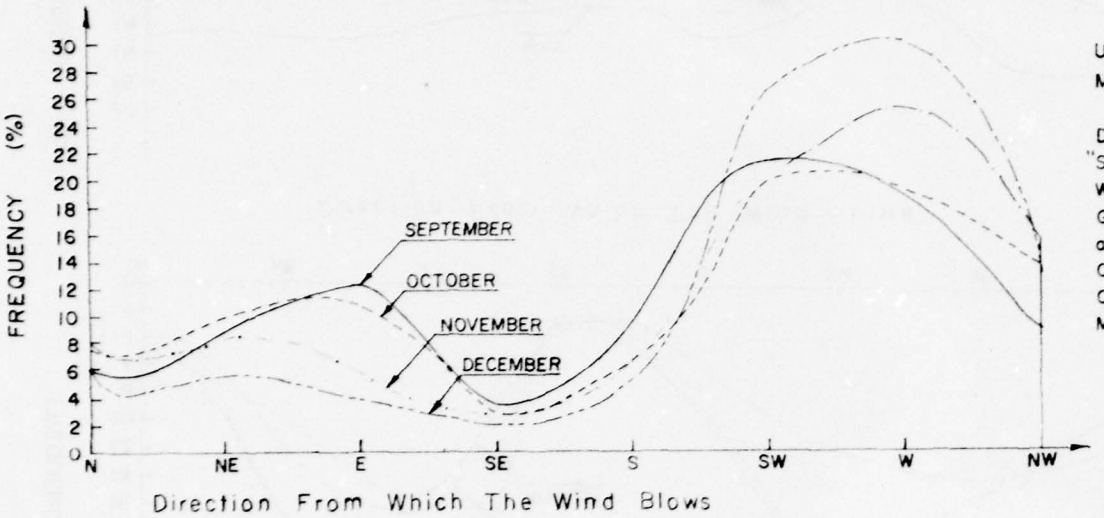
UNIV. OF WIS. - MADISON
MARINE STUDIES CENTER

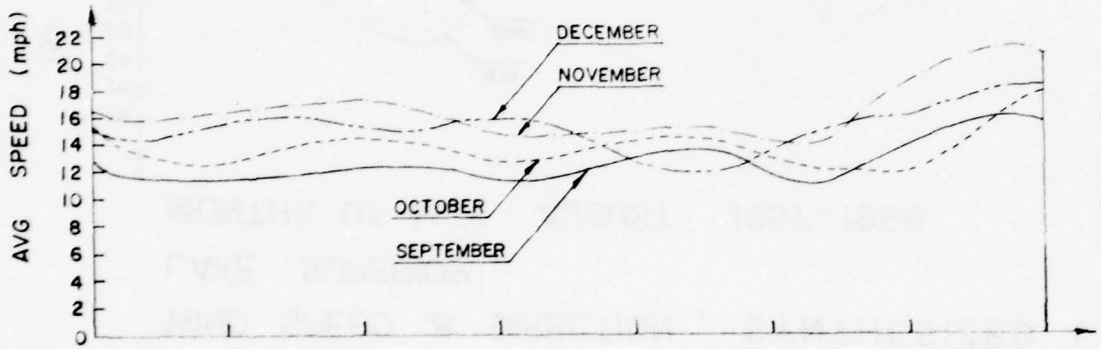
DATA FROM :
"Synthesized Winds and Wave Heights for the Great Lakes", T.L. Richards and D.W. Phillips, Climatological Studies, No 17, Canada Dept. of Transport, Meteorological Branch, 1970



(Figure 6) 21

WIND SPEED & DIRECTION SYNTHESIZED LAKE WINDS
LAKE SUPERIOR
MONTHS OF SEPTEMBER - DECEMBER 1957 - 1966





UNIV. OF WIS. - MADISON
MARINE STUDIES CENTER

DATA FROM :
"Synthesized Winds and Wave Heights for the Great Lakes", T.L. Richards and D.W. Phillips, Climatological Studies, No.17, Canada Dept. of Transport, Meteorological Branch, 1970

E. Waves

The wind speed and wind duration are two factors contributing to the appearance and growth of waves. The distance over which the wind blows (fetch) is another important factor which limits wave length and height. Greater wind speed, duration, and fetch length produce higher waves and longer wave lengths. If air temperatures above the water are lower than the water temperature, there will be more energy transfer from the wind to the water (and higher waves) than if the air is at the same or higher temperature than the water. Wave heights and wave lengths decrease due to bottom friction as waves travel toward the coast through shoaling water. For the Duluth-Superior and Keweenaw Upper Entry areas, fetch limitations and shoaling effects are considered in sections III, E and VI, E.

June, July, and August are the calmest months of the year on Lake Superior in terms of wave height statistics. September is a transitional month between the relatively calm summer and stormy fall months (Richards and Phillips, 1970).

Unconsolidated sediment particles lying loosely on the bottom of the lake are subject to movement by hydrodynamic forces in the water column above the sediment. A variety of formulas and diagrams have been derived in laboratory studies to show the relationship between particle size and the water velocities[1] required to move the particle or to put it into suspension. A recent review of these studies is included in Basco et al. (1974). The data are most applicable to loose, fine sand in situations where compaction has not occurred. Erosion of small silt

---

[1]Also referred to as critical velocity, incipient motion, or described in terms of critical shear stress at the sediment/water interface.

and clay particles is more difficult to analyze because of cohesive and adhesive forces. Where compaction of sedimentation has occurred, critical erosion velocities are higher than those for loose sediments of an equivalent size.

In our report, two approaches were taken in order to predict re-suspension potential. First, we assumed that the depth at which a given deep water wave is first influenced by bottom friction can be taken as a rough approximation of the depth beyond which re-suspension of sediment is not likely to occur. At this depth of influence there is essentially no wave-induced motion; therefore, no erosion of sediments by wave-induced water motion should occur. Secondly, using a diagram published by Allen (1965), we calculated orbital velocities at various depths for selected storm wave conditions and estimated the size of particles which would be eroded.

F. Weather Systems

For the Great Lakes region, areas of low pressure (cyclones) frequent the basin once every four to eight days (Phillips and McCulloch, 1972). More than half of these storms originate over the Rocky Mountains of Alberta, Montana, and Colorado. Data from Klein (1957) indicate the highest frequency of low pressure systems passing through the Lake Superior area occurs in April and in the time period from November through February. Principal storm tracks for low pressure systems in April cross the lake from northwest to southeast. From November through February, low pressure systems frequently move from west to east along the northern edge of Lake Superior. Klein's work was based on 40 years of data collected from 1899-1938. A more recent study by Reitan (1974) indicates some northerly shift in principal storm tracks for the 20 year period from 1951-1970. Primary low pressure tracks cross the Lake Superior region from west to east along the southern border of the lake in January, and along the northern border of the lake in April. Reitan's data indicate that more low pressure systems have passed over the lake in June, July, and October during the more recent period (1951-1970) than during the period of Klein's study (1899-1938).

The highest occurrence of high pressure systems (anti-cyclones) in the Lake Superior area occur from June through September (Klein, 1957). From May through July, principal anti-cyclonic tracks cross the region from north to south along the eastern boundary of the lake. Another primary track crosses south of the lake from west to east during the months of August and September.

Principal tracks of cyclonic and anti-cyclonic systems can help

predict wind-related physical processes beyond the few months of our limited observations. However, they must be used cautiously. The tracks were plotted from areas of maximum cyclogenesis, where the highest numbers of storm systems originate. The paths shown are few--Reitan plotted 4-5 major tracks for North America. Storm systems originating at sites other than those of maximum cyclogenesis may take different paths. The pathways described should be regarded only as a crude description of weather system movement in the Lake Superior region. The locations of principal cyclone and anti-cyclone tracks north or south of the Keweenaw Peninsula are summarized in Table 2.

Table 2

Location of Cyclonic & Anti-Cyclonic

Systems Near the Keweenaw Peninsula

Primary and Secondary Tracks[4, 3]

	Cyclones (Lows)		Anti-Cyclones (Highs)[1]	
Month	North of Keweenaw	South of Keweenaw	North of Keweenaw	South of Keweenaw
January	Primary[1]	Primary [1,2]		
February	Primary[1]	Primary		
March		Primary		
April	Primary[1]	Primary	Secondary*	
May		Primary		
June		Primary		
July	Primary[2]	Secondary		
August		Secondary	Secondary*	Primary
September		Secondary	Secondary*	Primary
October	Primary[2]	Primary	Secondary*	
November	Primary[1]	Primary		
December	Primary[1]	Primary		

[1]Data from Klein (1957).

[2]Data from Reitan (1974).

[3]Tracks generally move west to east or southwest to northeast. Exceptions (*) are tracks moving from northwest to southeast.

[4]Primary tracks are those which storm systems follow most frequently; secondary tracks are those tracks which storm systems follow less frequently.

III. Dynamics of Coastal Waters: Keweenaw North Entry

A. Summary Description of Physical Processes

The coast near the Keweenaw Waterway runs roughly northeast-southwest with no deep embayments or promontories and with no shelter for vessels except in the Waterway's Harbor of Refuge. This coast is exposed to winds and wave action with fetches ranging from 72 to 193 km from the southwest, west and northeast. The coastal currents off the North Entry generally flow to the northeast in summer and are probably part of the strong, well-defined Keweenaw Current.

Cyclonic systems to the north of the Peninsula, characterized by winds rotating counter-clockwise around a low pressure center, generate westerly winds along the coast. In the summer months these winds tend to accelerate the coastal current near the Upper Entry in a northeasterly direction to speeds approaching 50 cm/sec. They help maintain a constant or increasing water temperature nearshore and cause a southerly flow of water in the Keweenaw Waterway. Cyclonic systems north of the Waterway are probably most common from October to February, and in April and July (Table 2).

Occasionally, the coastal current reverses and flows to the southwest under the influence of easterly winds generated by anti-cyclonic systems located north of the Peninsula. This southwesterly flow usually coincides with periods of nearshore upwelling[1] and a northerly

---

[1] Upwelling is the slow movement of deep water to the surface along a coast, replacing the surface water which has moved offshore under the influence of a persistent longshore or offshore wind.

flow of water in the Waterway. Anti-cyclonic systems north of the Peninsula occur most frequently in April and in the time period from August through October (Table 2)

Wave action along the north shore of the Keweenaw Peninsula creates a littoral drift which is predominantly to the northeast during the spring, summer, and fall months. Breaking waves along the coast have contributed to severe erosion of clay banks in some sections. Accreting beaches on the southwest side of the North Entry and a fairly stable beach on the near north side appear to be exceptions to the erosion in this area. Current meter data and the sediment tracer studies described in Volume 2, indicate that dredge spoil disperses mainly to the northeast and offshore from the North Entry dumping sites. There is some evidence (based on observations by scuba divers) that fine sediment remains in suspension for some time at or above the thermocline. Stratification of nearshore waters begins in July and intensifies through the summer until a fall overturn in early December (Ragotzkie, 1974). However, occasional upwelling events and storm-induced mixing in the relatively shallow coastal areas temporarily break up this pattern of stratification.

The level of the lake at the North Entry may vary by as much as 0.5 m over a 24 hour period due to edge waves, storm set-up, and lake and channel seiches[1] induced by the passage of storm systems through the region. Over the past 100 years, the lake level has varied from 598.3 feet to 602.7 feet above the Great Lakes datum level (U.S. Department of Commerce, 1974). Seasonal high levels occur in August and September, and low levels occur in March and April.

---

[1]Periodic fluctuations of water level.

B. Winds

Wind data taken from along the Keweenaw Peninsula consist of some shipboard wind readings and records of winds at six hour intervals from the Portage Coast Guard Station near the Upper Entry. The Coast Guard anemometer is located at an elevation of 21.45 meters above the surface of the lake and 600 m inland from the coast. It has good exposure to winds from the west to north. The ten year climatological wind data in Figures 5-7, from Thunder Bay, Ontario represent the closest long term record of winds available. Therefore, a seasonal description of wind directions in the Keweenaw Area would probably be roughly similar to the description in Section II, D. The average wind speeds for westerly and northerly winds are probably higher at the Keweenaw Peninsula than Figures 5-7 incidate. Lake winds used in this report were synthesized from land wind readings at the Portage Coast Guard Station. This approach results in a very rough approximation of wind speed and reflects a lack of good over-water wind data.

C. Coastal Currents

Lake Superior is characterized by a counter-clockwise surface circulation pattern. This circulation was first noted by Harrington (1894) from the results of his drift bottle studies. Further studies have confirmed the general counter-clockwise circulation pattern and have also shown that the circulation intensifies along the northwest coast of the Keweenaw Peninsula (Ragotzkie, 1966, Hoopes et al., 1973).

On June 2, 1974, the Aanderaa recording current meter was placed approximately 1.5 km offshore of the North Entry. The analysis of the

offshore currents is based on the data collected during the period from June 2, to August 1, 1974. Data recorded after this period were lost with the current meter in a September storm.

During the months of June and July, the coastal current flowed to the northeast 43 days out of 60 (or 71% of the time) (Figure 8). The average speed in this direction was about 20-25 cm/sec., with a maximum velocity of 45-50 cm/sec. (Figure 9). The current speed seemed to intensify with strong, westerly winds.

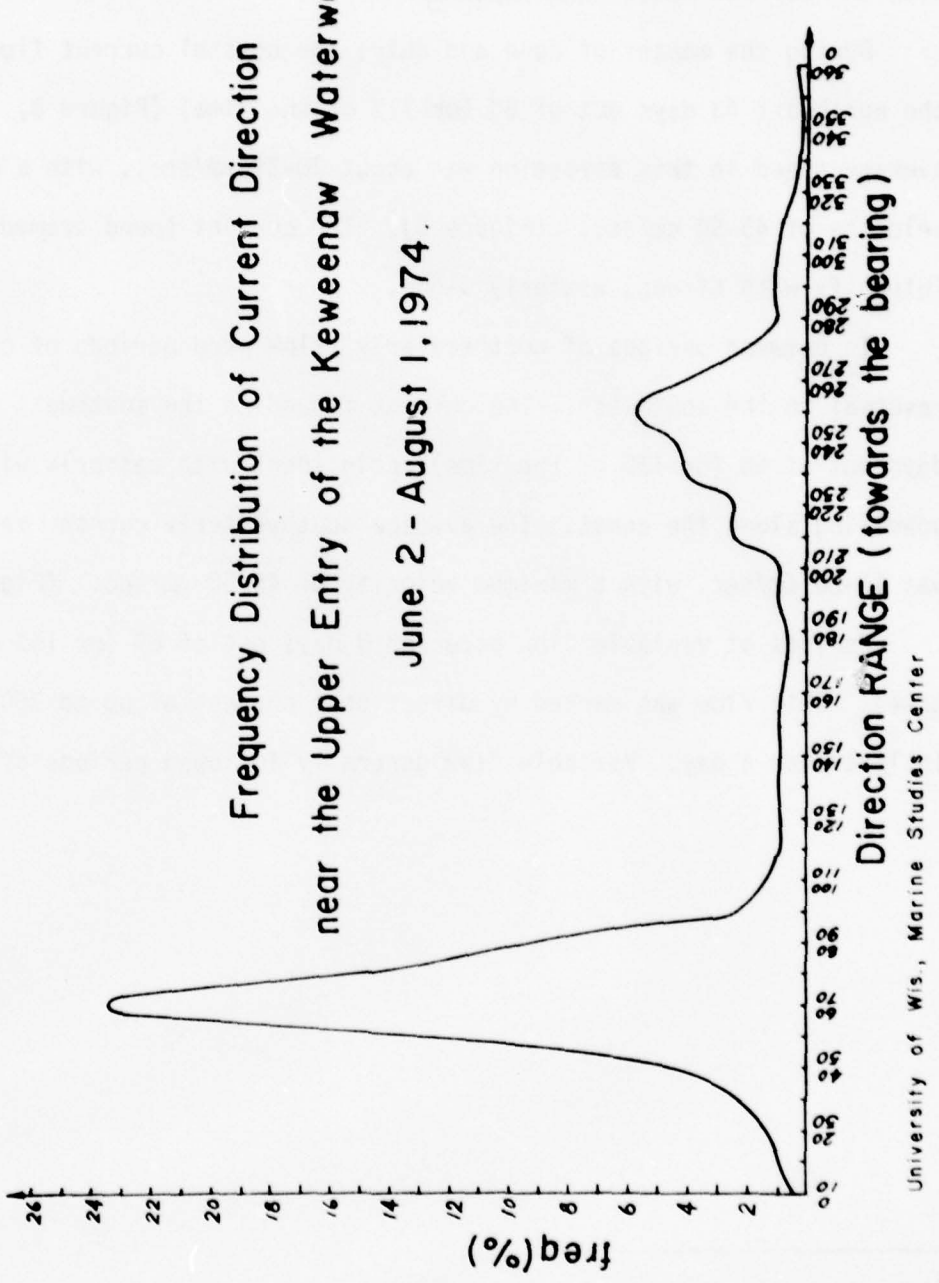
In between periods of northeasterly[1] flow were periods of current reversal to the southwest. The current flowed to the southwest eight days out of 60 (or 13% of the time), coincident with easterly winds and upwelling along the coast. The average southwesterly current velocity was 10-20 cm/sec. with a maximum velocity of 45-50 cm/sec. (Figure 10).

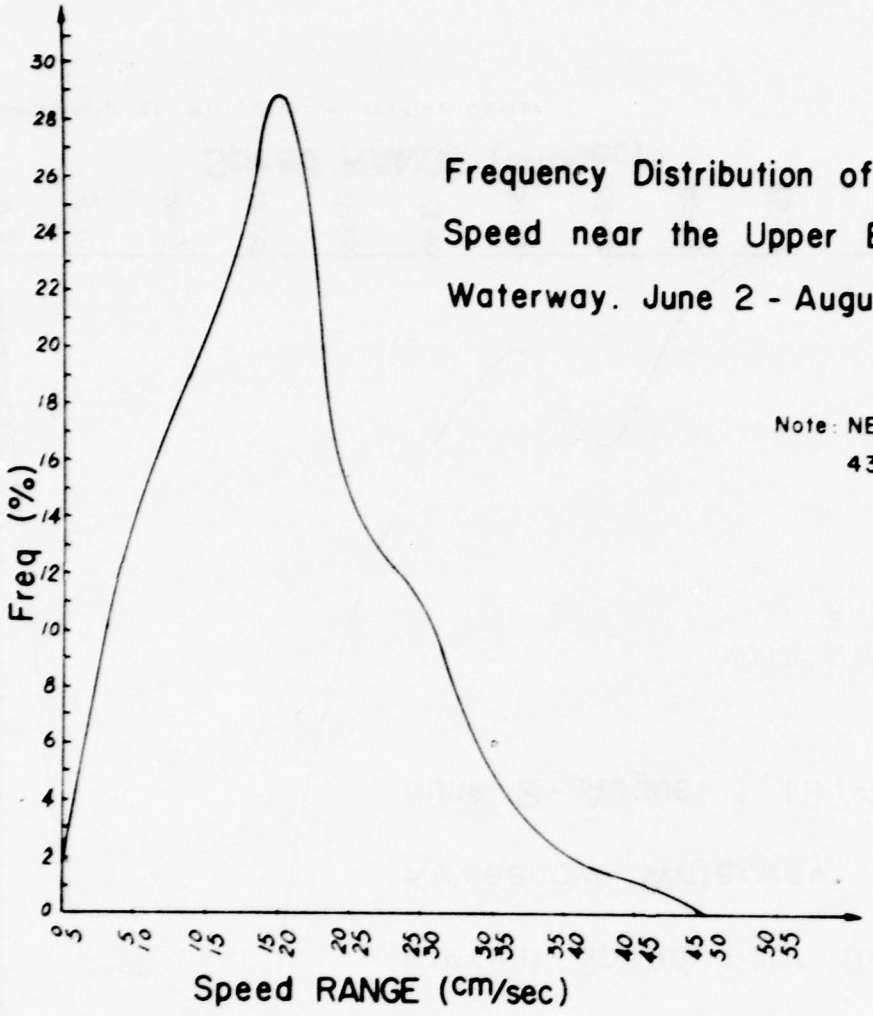
Periods of variable flow occurred 9 days out of 60 (or 16% of the time). This flow was marked by directional changes of up to 360 degrees in less than a day. Variable flow generally followed periods of upwelling.

---

[1]Directional references for currents are different than those for winds. A northeasterly flow is flow towards the northeast. Easterly winds are winds from an eastern direction (east, northeast, etc.)

(Figure 8)


Frequency Distribution of Current Direction
near the Upper Entry of the Keweenaw Waterway
June 2 - August 1, 1974
freq (%)
Direction RANGE (towards the bearing)
University of Wis., Marine Studies Center

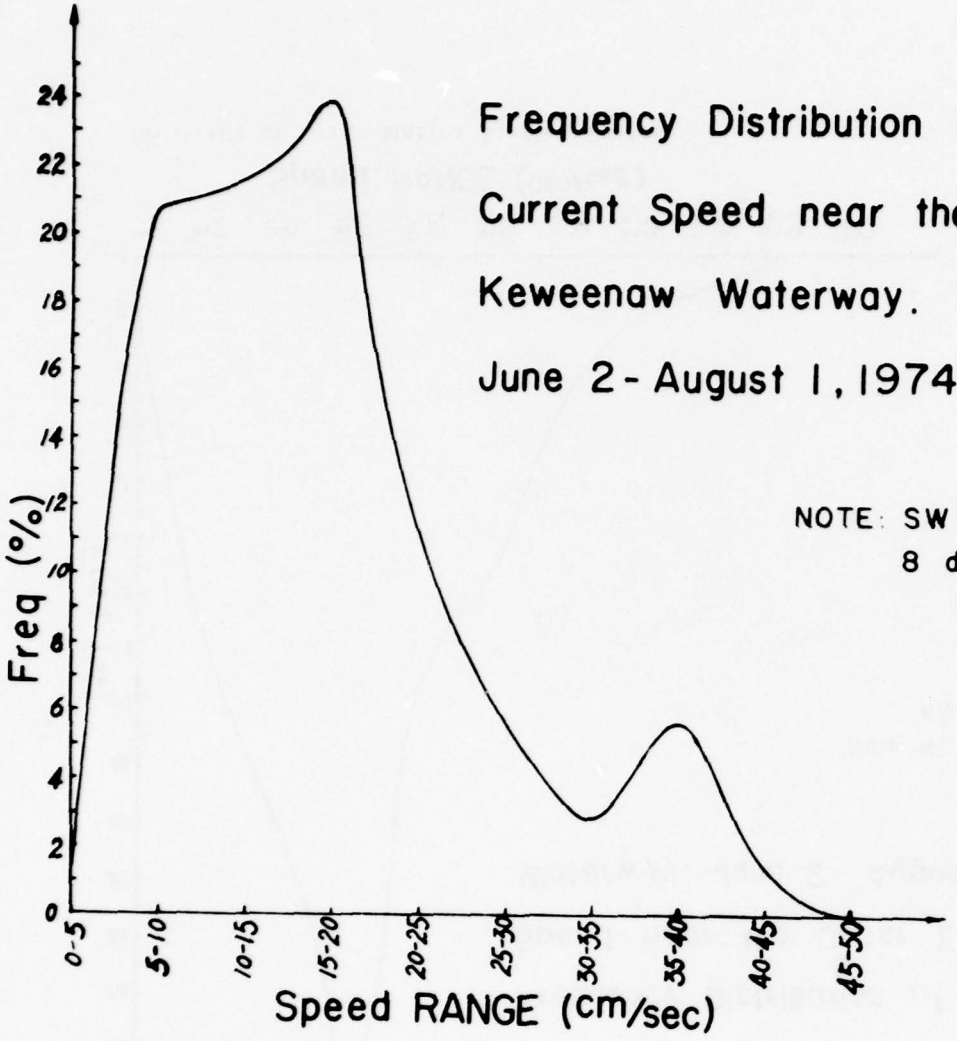


Frequency Distribution of the NE Current Speed near the Upper Entry, Keweenaw Waterway. June 2 - August 1, 1974.

Note: NE Current was predominant 43 days out of 60 days.

University of Wis., Marine Studies Center

(Figure 9)



Frequency Distribution of the SW Current Speed near the Upper Entry, Keweenaw Waterway.

June 2 - August 1, 1974.

NOTE: SW Current was predominant 8 days out of 60 days.

University of Wis., Marine Studies Center

D. Changes in Water Temperature and Currents

Three major upwelling events were recorded during the 60 day period between June 2 and August 1. These events occurred when high pressure systems were located north or northwest of the Waterway. In analyzing the changes occurring at the current meter, we have divided the 60 day period of recording into three, 20 day segments. The water temperature referred to in the following description of events was recorded 1.5 km northwest of the North Entry at the current meter which was 10 m below the surface in a water depth of 18 m at a distance of 1.5 km from the coast.

1. Description of Events

a. June 2-21, 1974

During the period of June 2-21, 1974, the lake temperature was rising--undergoing a gradual increase of 2°C to 16°C (Figure 11). Of interest to our study is the coastal current reversal on June 8. When the current reversed direction, from northeast to southwest, the water temperature dropped to less than 5°C, and the current speed suddenly decreased from over 30 cm/sec. to less than 10 cm/sec. The current then accelerated in a southwesterly direction. On June 10 the current flowed southwest at speeds exceeding 40 cm/sec., but near the end of the day the speeds began to decrease. By June 11, the flow of the offshore current had returned to a northeasterly flow, the water temperature had begun to increase, and the speed of the current had increased from approximately 10 cm/sec. to approximately 30 cm/sec.

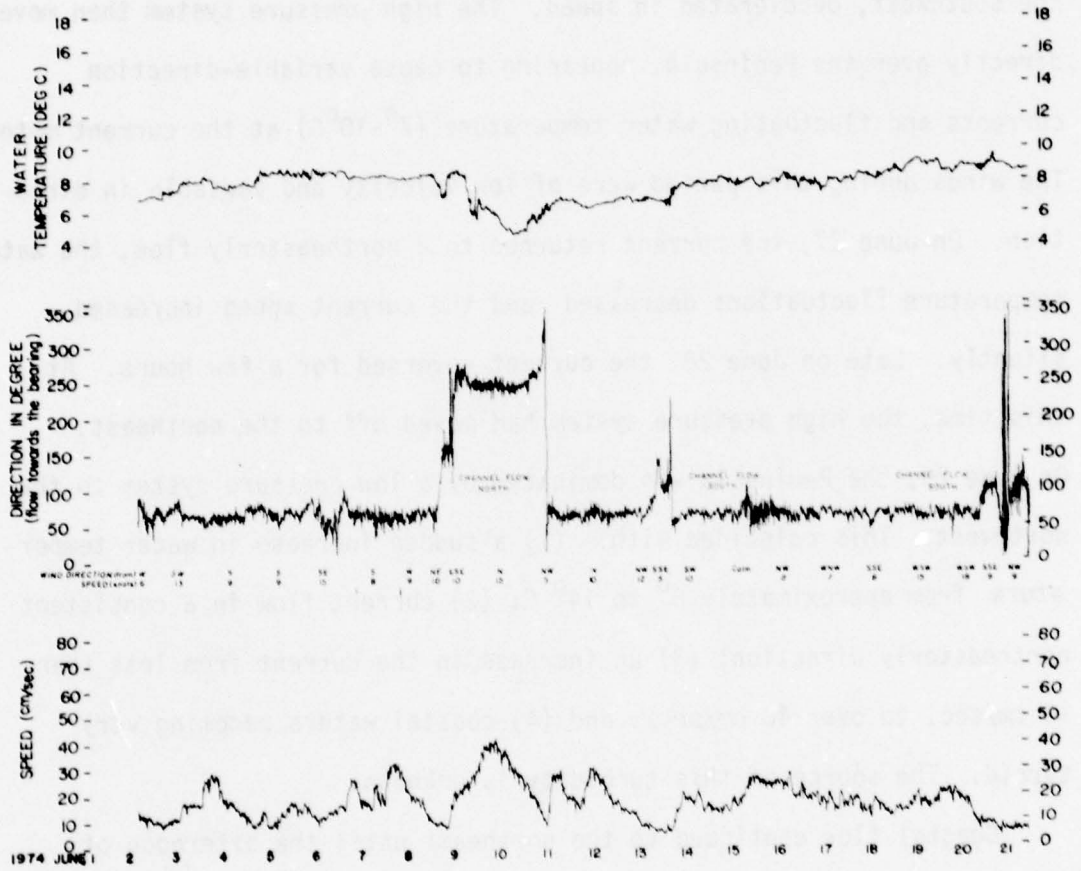
The cause of the current reversal on June 8 may have been due to a weak high pressure system located over the Keweenaw Peninsula and to the

shift of winds from the south at 13 km/hr. to the northeast at 20 km/hr.

The deceleration of the southwesterly current on June 10 corresponded with winds from the north and northwest at 21-24 km/hr. On the afternoon of June 11, the current had completely reverted to a northeasterly flow, and the winds were blowing from the west and northwest at 21 km/hr.

After this major upwelling event, the coastal current maintained a northeasterly flow through June 21 with two exceptions. Late in the evening of June 12, the current started to reverse but returned to a northeasterly flow. This fluctuation occurred when a weak high pressure system was located to the west northwest of the Keweenaw Waterway. A second shift in direction occurred on June 21. A weak high pressure system to the northwest of the Waterway and very still wind conditions may have been related to a sudden reversal of the current towards the southwest. This reversal lasted a few hours before the current returned to a northeasterly flow.

Nearshore Currents
in the Vicinity of the Upper Entry
Keweenaw Waterway, June 2–21, 1974



UNIVERSITY of WISCONSIN-MADISON, Marine Studies Center

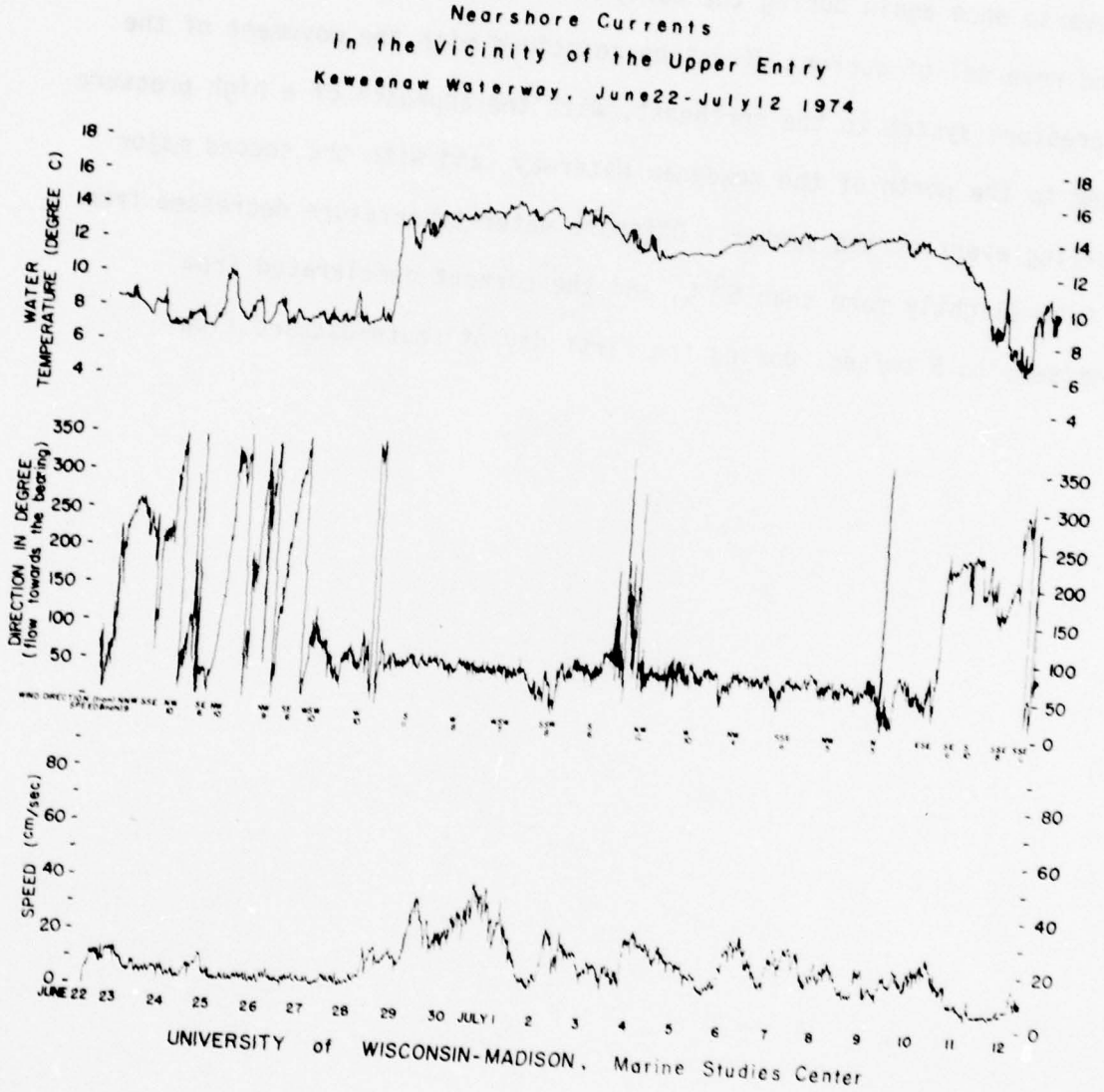
b. June 22-July 12, 1974

From June 22 to July 12, 1974, the coastal water was variable in flow direction and in temperature (Figure 12). A weak high pressure system moved into the Keweenaw area from the northwest on June 22. On June 23, it gained in strength. The current which was flowing to the southwest, decelerated in speed. The high pressure system then moved directly over the Peninsula, appearing to cause variable-direction currents and fluctuating water temperature (7^{o}-10^{o}C) at the current meter. The winds during this period were of low velocity and variable in direction. On June 27, the current returned to a northeasterly flow, the water temperature fluctuations decreased and the current speed increased slightly. Late on June 28, the current reversed for a few hours. At this time, the high pressure system had moved off to the northeast. On June 29, the Peninsula was dominated by a low pressure system to the northwest. This coincided with: (1) a sudden increase in water temperature from approximately 8^{o} to 14^{o} C; (2) current flow in a consistent northeasterly direction; (3) an increase in the current from less than 10 cm/sec. to over 40 cm/sec.; and (4) coastal waters becoming very turbid. The source of this turbidity is unknown.

Coastal flow continued to the northeast until the afternoon of July 3, when it changed to a southwesterly flow for a few hours. This corresponded with a slight decrease in water temperature and deceleration of current speed. At this time, a low pressure system dominated the Peninsula. The current reversal lasted only a few hours. On the afternoon of July 3, the current returned to a northeasterly flow. The water temperature began to increase once again, and the current accelerated from approximately 12 cm/sec. to 28 cm/sec.

Flow continued in a northeasterly direction until July 8. On that day, there was a sudden current reversal lasting less than 40 minutes. Following that, the current then returned to a northeasterly flow only to reverse once again during the early morning hours of July 10. The second reversal of current direction coincided with the movement of the low pressure system to the northeast, with the approach of a high pressure system to the north of the Keweenaw Waterway and with the second major upwelling event of the summer. Offshore water temperature decreased from 14^{o} C to slightly more than 6^{o} C, and the current decelerated from 25 cm/sec. to 5 cm/sec. during the first day of southwestward flow.

 (Figure 12)

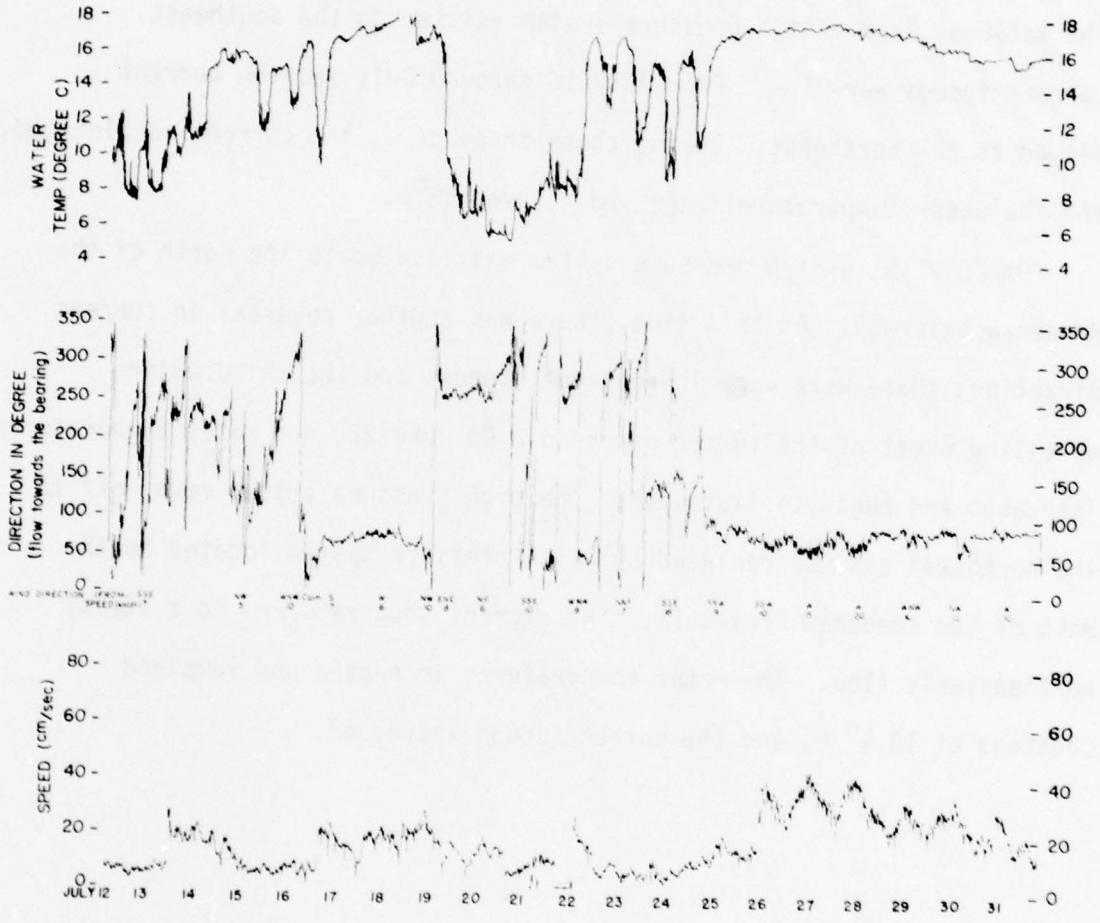

Nearshore Currents
In the Vicinity of the Upper Entry
Keweenaw Waterway, June22-July12 1974
WATER TEMPERATURE (DEGREE C)
DIRECTION IN DEGREE (flow towards the bearing)
SPEED (cm/sec)
JUNE 22 23 24 25 26 27 28 29 30 JULY 1 2 3 4 5 6 7 8 9 10 11 12
UNIVERSITY of WISCONSIN-MADISON, Marine Studies Center

c. July 13-31, 1974

The third time period of July 13-31, 1974 began with a period of upwelling (Figure 13). The current was moving in a southwesterly direction, but it soon became variable. The water temperature displayed a general rising trend with large temperature oscillations. During the period of variable flow, a low pressure system was located north of the Waterway, and a high pressure system existed to the southeast. Current speeds were low. From July 16 through July 18, the current flowed to the northeast. During these three days, the current accelerated, and the water temperature increased to over 18^{o}C.

On July 19, a high pressure system was located to the north of the Keweenaw Waterway. At this time, there was another reversal in current direction; there were very low current speeds; and the third major upwelling event of the summer occurred. On June 22, the water temperature increased and began to fluctuate. The high pressure system moved off to the northeast and was replaced by a low pressure system located northwest of the Keweenaw Peninsula. The current then returned to a steady northeasterly flow. The water temperatures increased and remained constant at 16.5^{o} C, and the current speed increased.

Nearshore Currents
in the Vicinity of the Upper Entry
Keweenaw Waterway, July 12-31 1974



UNIVERSITY of WISCONSIN - MADISON, Marine Studies Center

2. Current Direction

Figures 11-13 show that the summer coastal current is in one of the three regimes: (1) a steady northeasterly flow, (2) a steady southwesterly flow or (3) a variable unsteady flow at low speeds, changing directions.

When the current flowed southwesterly, a high pressure system was usually located to the north, and the winds were from the east. The average direction of the southwesterly flow was approximately 250 degrees true. Once the easterly winds stopped or changed direction or once a low pressure system moved into the area of study, the current tended to revert to a northeasterly flow. Variable flow generally occurred when a high pressure system was moving out of the area. Characterized by very low current speeds and fluctuating water temperatures, the variable flow usually occurred just after an upwelling event.

3. Current Speed

The speed of the northeasterly flowing current tended to increase as the wind velocity increased from the west. However, even under calm wind conditions, the current maintained its flow with an average velocity of approximately 20 cm/sec.

Changes in the speed of the current flowing southwesterly were more complicated. The speed varied from 1.5 to 45 cm/sec. When the winds were from the east and of low velocity, the speed of the current ranged from 15 to 20 cm/sec. When the winds from the east were strong, the average velocity ranged from 35 to 40 cm/sec. The southwesterly flowing current responded very quickly to changes in wind velocity. As easterly

winds increased, the current speed increased, and vice versa. When the wind changed direction, the current quickly decelerated and either returned to a northeasterly flow or flowed in a somewhat random fashion.

The speeds of the current were very low during variable flow conditions--averaging less than 10 cm/sec.

4. Predicted Dispersal of Fine Dredged Material

The current meter data from the dump site can be used to predict where suspended fine sediments from dredged material will go after dumping occurs. We assume that the suspended particulate matter will move with the predominant current flow, and eventually settle in other locations. Vector analysis of the current meter data indicates the sequential movements of water masses and provides some idea of the persistence (or variability) of flow in a given direction.

The results of this analysis show that suspended dredged material on the new dump site would generally move to the northeast with the predominant northeasterly coastal current. Depending upon the rate of settling, suspended material might move 12 to 20 km per day along the coast with the current influence by prolonged westerly winds.

With a southwesterly current influenced by easterly winds, suspended material will move in a southwesterly direction--perhaps as far as 15 km/day. Following an upwelling event, the coastal current near the North Entry is variable. Dredged material dumped at this time will not move far, and most suspended material will probably stay within a 1 to 2 km radius of the dump site--depending on particle size, amount of water turbulence and degree of thermal stratification present. Southwesterly flow and variable flow seldom had durations greater than three days in the summer of 1974. Northeasterly flow persisted for three to seven days.

When the coastal current is flowing to the northeast, the greatest dispersal of fine, suspended material from dredge spoil is likely to occur. Following an upwelling event, when the coastal current is variable in direction with low velocities, dispersal of suspended sediment will be lower than with either northeasterly or southeasterly currents.

5. Periodic Fluctuations in Water Velocity and Temperature

The currents recorded at our coastal current meter station occasionally flowed in almost every direction. To better understand the reasons for these directional variations as well as for the speed fluctuations, we divided the current data into a longshore flow along a major axis and an offshore/onshore flow along a minor axis. The major axis along a bearing 065 degrees (true) from north is the axis of northeastward flow and southwestward flow. The minor axis is defined arbitrarily as 90^{o} to the major axis. The components of flow in the axial directions were obtained by multiplying the current speed by the cosine of the angle between the current direction and the respective axis.

We made a spectral analysis of the axial components of current velocity to determine the fundamental periods of speed variations. By definition, the phase angle between the two axes is 90^{o}. The results of the spectral analysis are shown in Table 3.

The most important period of current speed fluctuation below 26 hours in the longshore direction is 11.66 hours. Inertial motion and the diurnal tide have some influence on current speed in this direction. The inertial period also influences offshore-onshore flow. The seiche has a lesser influence on movement of water in this direction. Many of the periodic fluctuations seen in the minor axial direction have also been observed in

the periodic fluctuations of water level, temperature and currents in the Keweenaw Waterway.

Periodic fluctuations in water temperature may indicate the influence of internal waves, lake seiches and tides. The diurnal and semi-diurnal tide were the major influence on water temperature for periods of one day or less during the two months of June and July. Analysis of a longer record would probably have indicated the importance of upwelling or other long-period phenomena in affecting water temperature.

Table 3

Fundamental Periods of Nearshore Water Velocity and Temperature Fluctuations

Water Temperature Periods(hours)	Theoretical Periods(hours)	Major Axis[1] Periods(hours)	Minor Axis[2] Periods(hours)	Probable Explanation
24.84 (1)	25.00[3]	25.39 (3)		diurnal tide, Lake Superior[3]
20.96 (3)				
	17.00	16.99 (2)	16.99 (2)	inertial period, Lake Superior
		16.21 (4)	15.76 (1)	
14.84 (4)				
12.35 (2)	12.50[3]		12.95 (6)	semi-diurnal tide, Lake Superior[3]
11.66 (5)		11.66 (1)	11.53 (3)	
	8.00[3]		7.75 (8)	1st longitudinal mode, Lake Superior seiche[3]
	3.75[3]		3.77 (5)	3rd longitudinal mode, Lake Superior seiche[3]
	2.30[3]		2.33 (7)	1st transverse mode, Lake Superior seiche[3]
			1.38 (4)	

Note: The numbers in parenthesis reflect relative importance in terms of energy present. The number (1) indicates highest level of energy present.

[1]Axis aligned with 065° (true), parallel to the Keweenaw coast at the Upper Entry.

[2]Axis aligned with 155° (true), perpendicular to the coast.

[3]Calculation and explanation of periodic variations from Mortimer and Fee, 1972.

E. Wave Action

The north and west coasts of the Keweenaw Peninsula are exposed to prevailing westerly winds blowing over long fetches. Wind-generated waves erode and build Keweenaw beaches depending on the beach slope, nearshore bathymetry, wave height, sediment texture, and other factors. Waves also stir up bottom sediments and influence the sorting of different sized particles.

Wind moving over the water surface transfers appreciable amounts of energy which travel in the form of waves as much as $\pm 45^{o}$ to the mean wind direction (Kinsman, 1965). Off open ocean coasts, this energy transfer is unhindered by the presence of adjacent land masses. For lakes, bays and estuaries the irregular shorelines enclosing the basin have a limiting effect on the energy transfer along fetches at some angle to the mean wind direction. Therefore, an effective fetch length which accounts for the constricting effects of the shoreline must be used in some areas. For wave estimates at the North Entry and at Duluth-Superior, we used the method for calculating the effective fetch which is described in the Shore Protection Manual (Corps of Engineers, 1973). This method assumes: (1) that wind moving over the water transfers energy to the water in the wind direction and in all directions on either side of the wind direction, and (2) that the energy transfer along any radial to the wind direction is modified by the cosine of the angle between the radial and the wind direction.

At the North Entry, the effective fetches range from 107 km (northwest) to 169 km (northeast). Table 4 shows that the effective fetches at the North Entry are similar to those at Eagle Harbor, 48 km to the northeast. A wave recorder was installed at Eagle Harbor by the Hydraulics Laboratory, National Research Council of Canada in 1965 and 1966 (McCulloch and Derco, 1968). The wave data from this recorder, shown in Table 5, can be used for an approximate description of the deep water wave conditions that occur near the North Entry during the summer and fall months.

Table 4

Effective Fetch at the Keweenaw Waterway-North Entry and at Eagle Harbor

Direction	Effective Fetch (km) Eagle Harbor	North Entry
N	122	130
NW	107	120
W	157	146
NE	169	179

Since waves are random in height and period, the wave data presented in Table 5 are a statistical representation of estimated wave conditions. The smallest waves are ignored and the average height of the highest one-third of the remaining waves is called the significant wave height. The wave data cover a period of time from July 22 to November 12, 1965 and from May 19 to December 4, 1966. In 1965, the wave recorded was operational 25% of the measurement period. In 1966, it was operational 71% of the time. As a result, this data should be used only to indicate trends and approximate wave conditions. The statistics on maximum yearly wave occurrence were based on the assumption that wave conditions from December

to May are the same as the recorded conditions from May to December. This assumption may not be valid. Climatological wave statistics indicate that large waves can be expected more frequently in the winter months (Richards and Phillips, 1970).

Wind data from the Portage Coast Guard Station at the North Entry was used with wave forecasting techniques from the Shore Protection Manual to estimate wave heights and periods for selected meteorological conditions. Figure 14 shows the depth of influence hindcast for deep water waves near the North Entry when the significant wave heights were probably greater than 1.5 m during storms occurring between October, 1973 and July, 1975.

The significant waves often occur in groups which are nearly periodic. The average period of these groups is called the significant period, and it was used to calculate the wave lengths of the significant waves. The effect of wave-induced water motion on sediments at rest was assumed to be limited to depths less than half the wave length--the depth of influence (Figure 14). While waves will probably not cause sediments to be re-suspended at depths greater than the depth of influence, sediment texture and particle cohesion may sometimes prevent re-suspension at shallower depths. Therefore, the depth of influence is a conservative, maximum value for predicting re-suspension of sediments due to waves.

The maximum significant wave height in deep water off the North Entry was probably close to 3 m with a 38 m depth of influence during the storms of 1973-1975 considered in Figure 14. This significant wave height corresponds to a deep water wave length of 76 m and a period of seven seconds. Based on this data, the maximum individual wave height was probably about 6 m, less than the 10 m wave height expected at Eagle Harbor once a year (Table 5).

Table 5

Deep Water Wave Data for the Eagle Harbor Area of Lake Superior

	Median Significant Wave Height (m)	1% Significant Wave Height (m)	Median Value of Peak Wave Lengths (m)	1% Value of Peak Wave Lengths (m)
Up to Sept. 15	.5	2.0	18.3	68.6
Sept. 16 to 30	1.1	3.0	21.4	76.2
Oct. 1 to 31	1.0	5.0	24.4	106.9
Nov. 1 to end	1.1	6.4	33.5	123.8
Entire Season	.6	4.3	25.9	113

Significant Wave height to be expected once a year . . . . . 8.8 m

Maximum observed individual wave height . . . . . 10.4 m

Peak wave length to be observed once a year . . . . . 191 m

Data adapted from Ploeg (1971).

(Figure 14)

DEPTH OF INFLUENCE FOR WAVES
AT THE UPPER ENTRY, KEWEENAW PENINSULA
Significant Wave Heights Greater Than 1.5 Meters From October, 1973 to July 1975
WAVES FROM THE
× Northwest
O North
● West
DEPTH OF INFLUENCE (Meters)
0
10
20
30
40
50
1.5
2.0
2.5
3.0
SIGNIFICANT WAVE HEIGHT (Meters)
University of Wis., Marine Studies Center

Similar, high, long period waves probably occurred on at least three and possibly 12 occasions at the North Entry from October, 1973 to July, 1975. Table 6 summarizes calculated wave characteristics during the occasion of strongest wave action for each of the three primary directions at the North Entry: north, northwest and west. At 18 m depths, water motion was probably sufficient during these storms to move loose particles between 0.02 and 8 mm diameter. At 24 m depth, particles from 0.02-6 mm diameter may have been part of the bed-load transport due to wave action. These very rough estimates[1] of sediment movement give some idea of the influence of waves on the Keweenaw coast.

The mean grain size of 54 dredge spoil samples collected from scows in the North Entry, ranged from fine sand (.25 mm) to silt and clay (.06 mm) (Volume 2, Figure 69). The wave action described in Table 6 appears to have been strong enough to transport unconsolidated portions of this spoil--all of which were dumped in depths of less than 24 m. This is consistent with observations made by our divers on the experimental dump site at 18 m depth near the North Entry. Mounds of dredge spoil observed on the bottom in October, 1974 during the period of dumping activity, were not detected the following May during extensive underwater coverage of the dump site.

---

[1] Relationship between flow velocity and grain size was obtained from Allen (1965).

Table 6

Wave Characteristics for Three Storm Events at the Keweenaw Upper Entry

Date	Ave. Wind Speed m/sec.	Duration (hours)	Wind Direction from	Significant Wave Height (m)	Significant Period (Sec.)	Deepwater Wavelength (m)	Maximum Depth of Influence (m)
11/30/73	15.20	6-18	NW	2-3	6-7	54-79	40
1/12/75	14.75	3-9	W	1-4	5-8	33-100	50
1/19/75	11.62	6-12	N	1-3	4-7	30-70	35

F. Conclusions

If in-lake spoil disposal occurs offshore when the coastal current is flowing to the northeast, the initial dispersal of suspended fine sediment may approach 20 km/day. This flow can be expected when westerly winds are blowing and a low pressure system is located north of the Peninsula. Less initial dispersal of suspended spoil is likely to occur: (1) during periods of southwesterly or variable current flow, (2) following coastal upwelling, or (3) before thermal stratification becomes well established in early August.

Dredge spoil disposal near the North Entry in depths of 24 m or less will probably result in dispersion of the spoil deposits by wave and current energy. Dredge spoil dumped at depths greater than 95 m will not be subject to re-suspension by wave energy. This conclusion is based on the depth of influence calculated from the peak wavelength expected once a year (Table 5).

Coastal current speeds and directions are influenced by wind stress, seiching, and the small diurnal tide. Water temperature fluctuations are influenced by wind stress and the diurnal tide. Other factors, such as internal waves, will affect water temperature. Some of the periodic variations observed in water velocity and temperature remain unexplained.

IV. Dynamics of the Keweenaw Waterway

A. Summary Description

The Keweenaw Waterway is approximately 35 km in length with a minimum maintained depth of 7.6 meters. It crosses the Keweenaw Peninsula from northwest to southeast and connects western Lake Superior to Keweenaw Bay (Figure 3). Near the midpoint of the Waterway is Portage Lake with characteristic depths of 9-14 meters and a maximum depth of 16.5 meters. The width of the Waterway varies from 153-760 meters and has a total volume of approximately 2.86×10^7 cubic meters, excluding Portage Lake which has an approximate volume of 2.88×10^8 cubic meters.

Flow in the Waterway is caused by differences in water levels along the length of the Waterway. Changes in water levels are due to the influence of wind and to alterations in air pressure and channel seiching.

In the summer of 1974, the Waterway had a southerly flow 65% of the time with an average observed speed of 2-4 cm/sec. and a maximum observed speed of 31 cm/sec. The average observed speed of the northerly flow was 5-7 cm/sec.

Over a 12 hour period water levels varied as much as 50 cm at the North Entry, 10 cm at Houghton, and 71 cm at the South Entry. Water level fluctuations were periodic with the eight-hour period of Lake Superior's longitudinal seiche (first mode), the dominant influence at the North Entry and Houghton. The longitudinal and transverse seiches of Lake Superior (first mode) were dominant at the South Entry. The longitudinal lake seiche appears to move through the Waterway from north to south. The transverse lake seiche appears to move in the opposite direction.

Waterway currents change direction, water levels rise or fall, and the

water temperature changes as lake water displaces channel water or vice versa. During the summer of 1974, we observed Lake Superior water moving to the south as far as the MTU dock in Houghton. Flow in the Waterway appears to be related to the passing of weather systems and to nearshore processes in the lake. On 19 days, a plume of channel water was observed extending into Keweenaw Bay from the South Entry, indicating southerly flow in the Waterway. On 15 of these occasions, a low pressure system was located in the area or north of the Peninsula. During the other four days, a high pressure system was either directly over the Waterway or southwest of the Waterway. In addition, on 13 of the 19 days, the coastal current off the North Entry was steady or accelerating to the northeast, and on 14 occasions, the water temperature nearshore was steady or rising.

On nine other days, a plume of channel water was observed flowing out of the North Entry. On each of these days, a high pressure system existed over the area, or northwest of the Peninsula, and coastal upwelling off the North Entry was occurring or had just occurred.

B. Water Level Fluctuations

Any body of water has natural frequencies of water level fluctuations (or seiches) induced by atmospheric perturbations such as passing storm systems. These frequencies are determined by the water depth and the horizontal dimensions of the water body. Mortimer and Fee (1972) describe some of Lake Superior's seiche periods. These are shown in Table 7 along with the dominant periods observed in water level records from the North Entry, Houghton, and the South Entry (see Figure 3 for locations of water level recorders). In general, the predominant water level fluctuation periods found at each station along the Waterway were very similar.

Table 7. Periodic Water Level Fluctuations
Dominant Periods

Theoretical Lake Superior Periods (hours)	Probable Cause	North Entry Periods (hours)	Houghton Periods (hours)	South Entry Periods (hours)
25.00*	diurnal tide*	24.43 (3)**		
16.28	inertial period	16.41 (12)		
12.43*	semi-diurnal tide*	12.48 (2)	12.68 (3)	
7.90*	1st mode longitudinal seiche*	7.89 (1)	7.96 (1)	8.00 (2)
3.80*	3rd mode longitudinal seiche*	3.74 (5)		
			3.13 (4)	3.14 (3)
				2.99 (4)
2.34*	1st mode transverse seiche*	2.28 (4)	2.32 (2)	2.30 (1)
		1.85 (7)	1.79 (5)	
				1.59 (5)
		1.47 (6)		1.47 (6)
		.975 (8)		
.75	Portage Lake Seiche	.742 (11)	.723 (7)	.721 (9)
		.565 (9)	.561 (6)	.556 (8)
				.410 (7)
		.321 (10)	.324 (8)	

*Calculated periods and explanation of sources from Mortimer & Fee, 1972
**The numbers in parenthesis indicate the relative strength (or dominance) of a period. The number (1) indicates greatest strength.

1. North Entry

The total variation of water level at the North Entry was less than 5 cm to more than 50 cm in a 12 hour period. Visually, there appeared to be a strong 19.3 minute component--probably due to the seiche period of the North Entry harbor mouth--but spectral analysis showed that this period was greatly over-shadowed by lower frequency fluctuations. The strongest period we observed at the North Entry was the 7.89 hour fluctuation. This period corresponds with the 7.90 hour 1st mode of the longitudinal seiche described by Mortimer and Fee (1972).

2. Houghton

The total variation of water level at Houghton was relatively minor, seldom exceeding 10 cm. Fluctuations of 6 cm were more typical even when the North and South Entries were experiencing fluctuations of 24 cm or more. Spectral analysis of water level records taken at Houghton showed strong eight and 12.5 hour fluctuations. Of interest is the apparent increase in strength of the 2.3 hour period as compared to the North Entry data. Furthermore, there is a continued dominance of the eight hour seiche as compared to that which was found at the North Entry.

3. South Entry

South Entry water levels fluctuated from an average of 10 cm to over 71 cm following a particularly violent thunderstorm on June 30, 1974. The South Entry water level variations were characterized by a strong 2.3 hour period, which was discerned visually on the water level records. An 8.0 hour period also dominated at the South Entry. Periods of less than one hour had considerably less energy than the longer periods.

4. Phase and Coherence Between Stations

When data from two stations are analyzed over the same time period, the phase coherence and the phase angle for various water level fluctuation periods can be determined. A positive phase angle means that the first station listed leads the second station. A negative phase angle means the second station leads the first station. A coherence near 1.00 means that there is a strong correlation between stations for the given water level fluctuation period. In Table 8, phase and coherence are examined for the 2.3 and 8.0 hour water level fluctuations between the three stations in the channel. From this analysis, we can deduce the following information. The 8.0 hour water level fluctuation first arrives at the North Entry and travels south to the South Entry. Conversely, the 2.3 hour seiche first arrives at the South Entry and moves north to the North Entry.

It appears that the Waterway seiches generate shallow water progressive waves which move through the channel. The velocity of these waves can be determined from the equation $V = \sqrt{gD}$ (Chow, 1959). The velocity is V, the acceleration of gravity is g and the average channel depth is D. Using this equation, these waves are found to move through the channel at speeds of approximately 1350 cm/sec. (30 mph).

Table 8

Phase Angles and Phase Coherence for Three Stations Along the Keweenaw Waterway

	North Entry vs. Houghton	Houghton vs. South Entry	North Entry vs. South Entry
8.0 hour period phase angle	153.2	60.5	218.9
8.0 hour period phase coherence	.954	.973	.926
2.3 hour period phase angle	-96.9	-188.0	-271.2
2.3 hour period phase coherence	.648	.949	.413

C. Water Temperature Fluctuations

During periods of coastal upwelling, when cold water is found close to shore near the North Entry, the water temperature at the North Entry does not immediately decrease. On three occasions when coastal upwelling occurred, we noted that the water temperature at the North Entry increased at first and then dropped. The reason for this phenomenon may be that with the onset of upwelling, nearshore water is transported offshore. At the same time, the channel water flows northward, and since channel water is normally warmer than Lake Superior water, an initial increase in temperature can be observed at the North Entry. Approximately 24 hours after the onset of upwelling, cold Lake Superior water moves south into the channel beneath the warm channel water. When this first occurs, the measured water temperature at the North Entry oscillates by as much as 5^{o} C. As upwelling continues, the Lake Superior water moves further south into the Waterway, sometimes as far as the Lily Pond. During the summer of 1974, cold water was never observed to flow as far south as

Houghton. It appeared that the lake water in the northern regions of the Waterway formed a wedge of cold water beneath the warm, northerly flowing channel water. Two drogue measurements conducted at the North Entry during periods of upwelling showed that the upper layers of channel water moved north out of the Waterway and then moved either southwest or northeast along the coast. At the same time, the lower layers of lake water appeared to move slowly south into the Waterway.

D. Channel Flow

1. Direction

Twenty-nine drogue studies in the channel, daily visual observations, and frequent photographic aerial flights show that the Waterway current generally flows south. During 70 days of observation, the channel current flowed to the south approximately 65 percent of the time. Between June 11 and August 13, 1974, 30 aerial photographic flights were made. On 19 of the 30 flights, we observed a plume of brown channel water at the South Entry. On 10 of the 30 flights, we saw a plume of channel water at the North Entry. Observations during one flight showed clear water at both Entries. We assume that a plume of channel water at an Entry depicted the overall flow of channel water for at least the previous few hours. Figures 15 and 16 show a plume of channel water entering the lake at the North Entry.

It appears that the direction of channel flow depends upon pressure systems and the wind direction. On all days when a plume of channel water at the South Entry was observed, the wind had a north or west component. Plumes of brown channel water at the North Entry were observed mainly when the wind had an easterly component.

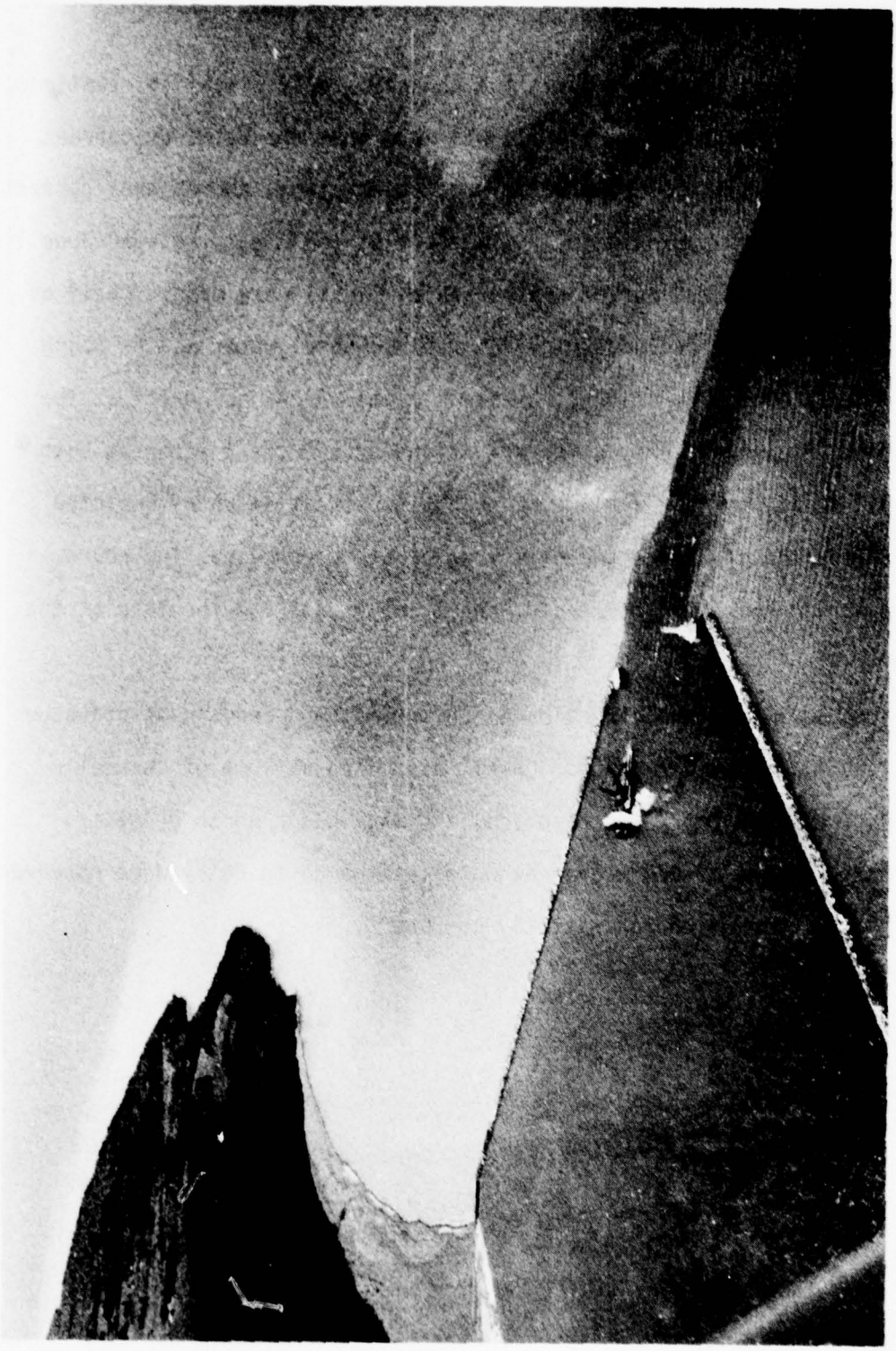


Figure 15 Nearshore Turbidity and Waterway Outflow--Keweenaw Upper Entry

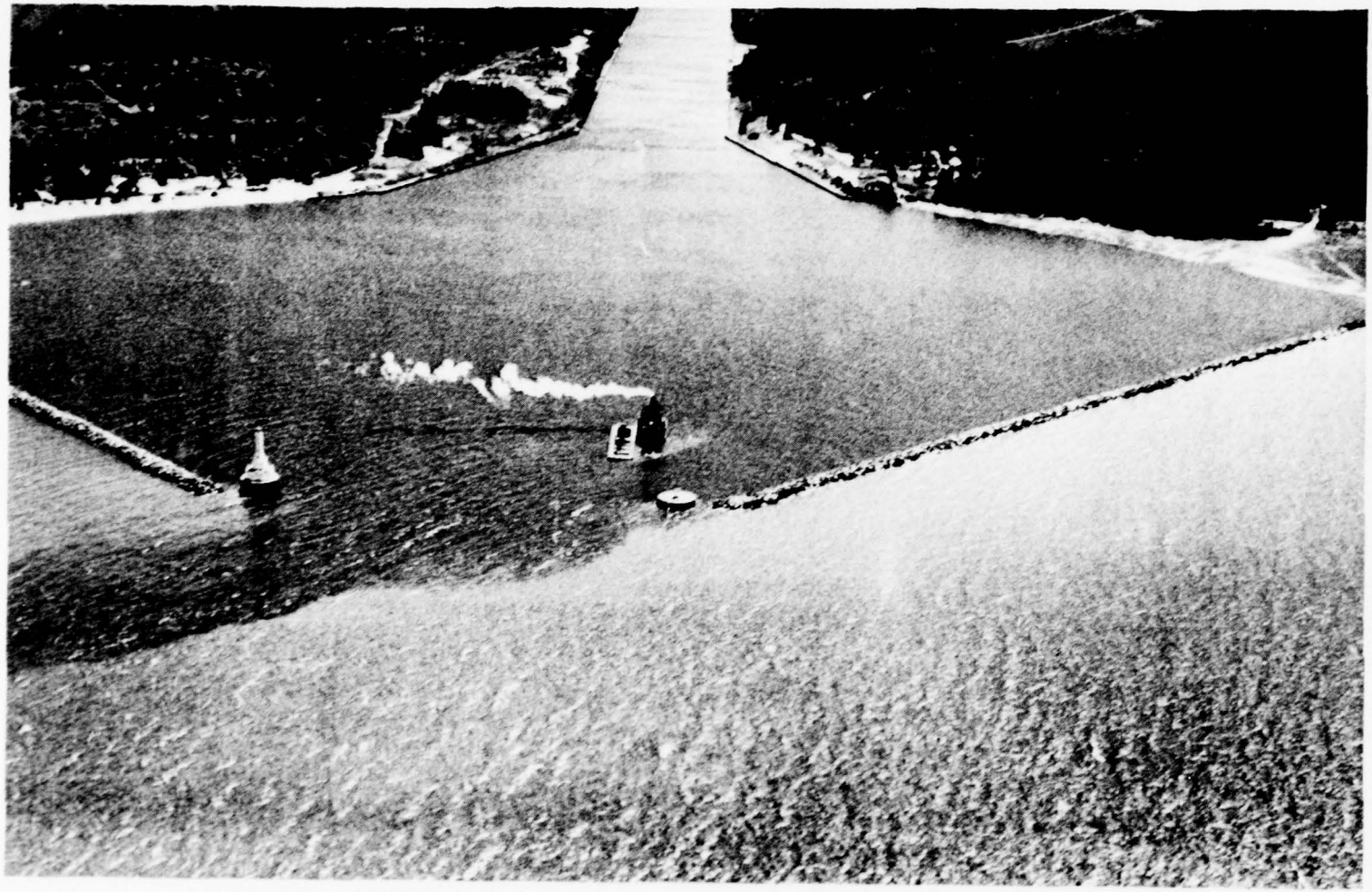


Figure 16 Dredge GAILLARD Operating in the Keweenaw Upper Entry During a Period of Waterway Outflow--June 11, 1974

2. Speed

A small amount of data on channel currents was collected and analyzed for two periods: June 6-11 and August 5-11, 1974. During the five days in June, the current ranged in speed from 0-31 cm/sec. with an average velocity of 4.3 cm/sec. Flow was predominantly towards the south. During the August period, northerly current velocities averaged 7 cm/sec. and southerly current velocities averaged 2 cm/sec.

3. Estimate of Volumetric Transport

A rough estimate of volumetric flow in the Waterway during June 6-11 and August 5-11, 1974 is shown in Table 9. This estimate is based on the following assumptions:

(1) The channel at MTU is rectangular in cross-section with a width of 91.5 m and a uniform depth of 8.85 m.

(2) The channel water flowed to the north 35 percent of the time and to the south 65 percent of the time from June 6-11.

(3) Channel water flowed to the north 54 percent of the time and to the south 46 percent of the time from August 5-11.

(4) From June 6-11, the average channel velocity was 4 cm/sec. during southward flow and 5 cm/sec. during northward flow.

(5) From August 5-11, the average channel velocity was 2 cm/sec. during southward flow and 7 cm/sec. during northward flow.

(6) The current was steady in the direction of flow.

During the August 5-11 period, coastal upwelling was occurring near the North Entry. A greater difference in northerly and southerly average current velocities during this period as compared to the average currents for the June 6-11 period, accounts for the greater net flow in the August period than in the June period.

Table 9. Estimate of Keweenaw Waterway Average Flow Rate

Date	Flow Direction	A (m^2)	V	Q = AXV (million m^3 water/day
June 6-11, 1974	To the South	810	4	1.8
	To the North	810	5	1.2
	Net Flow to the South			0.6
Aug. 5-11, 1974	To the South	810	2	0.6
	To the North	810	7	2.6
	Net Flow to the North			2.0

4. Channel Flow Fluctuations

Channel current meter data was digitized at 2.5 minute intervals over the period of August 5-11, 1974. Velocity was arbitrarily positive if the channel flow was to the north and negative if the channel flow was to the south. A spectral analysis was then made on this data to determine the major periods of channel current fluctuations. The results are listed in Table 10.

Table 10. Dominant Periods of Channel Current Fluctuations

Period	(Hours)	Probable Explanation
12.15	(3)	Semi-diurnal tide, Lake Superior
8.92	(5)	
7.68	(1)	1st mode, transverse Lake Superior seiche
2.29	(2)	1st mode, transverse Lake Superior seiche
1.86	(4)	
1.79	(6)	
.78	(7)	Portage Lake seiche

Note: The number in parentheses to the right of the period of fluctuation gives a rough indication of the importance of the periodic current fluctuation. The number (1) indicates greatest significance.

V. Dynamics of Offshore Waters: Duluth-Superior Area

Most of the description of physical transport processes in the Duluth-Superior area is based on the research of Michael Sydor, University of Minnesota-Duluth. Sydor's study combined analysis of ERTS satellite photos, ground truth turbidity measurements and continuous current measurements at three stations in 1973 and five stations in 1974. Bottom currents were recorded by current meters mounted one meter above the lake floor. Surface currents were measured at two meter depths. The threshold sensitivity of the current meters was two cm/sec. The directional accuracy was within 15 degrees. Current meter readings of speed and direction were recorded every 15 minutes.

Our measurements at Duluth-Superior included vertical temperature profiles with a bathythermograph (BT), surface and bottom water temperatures and depths.

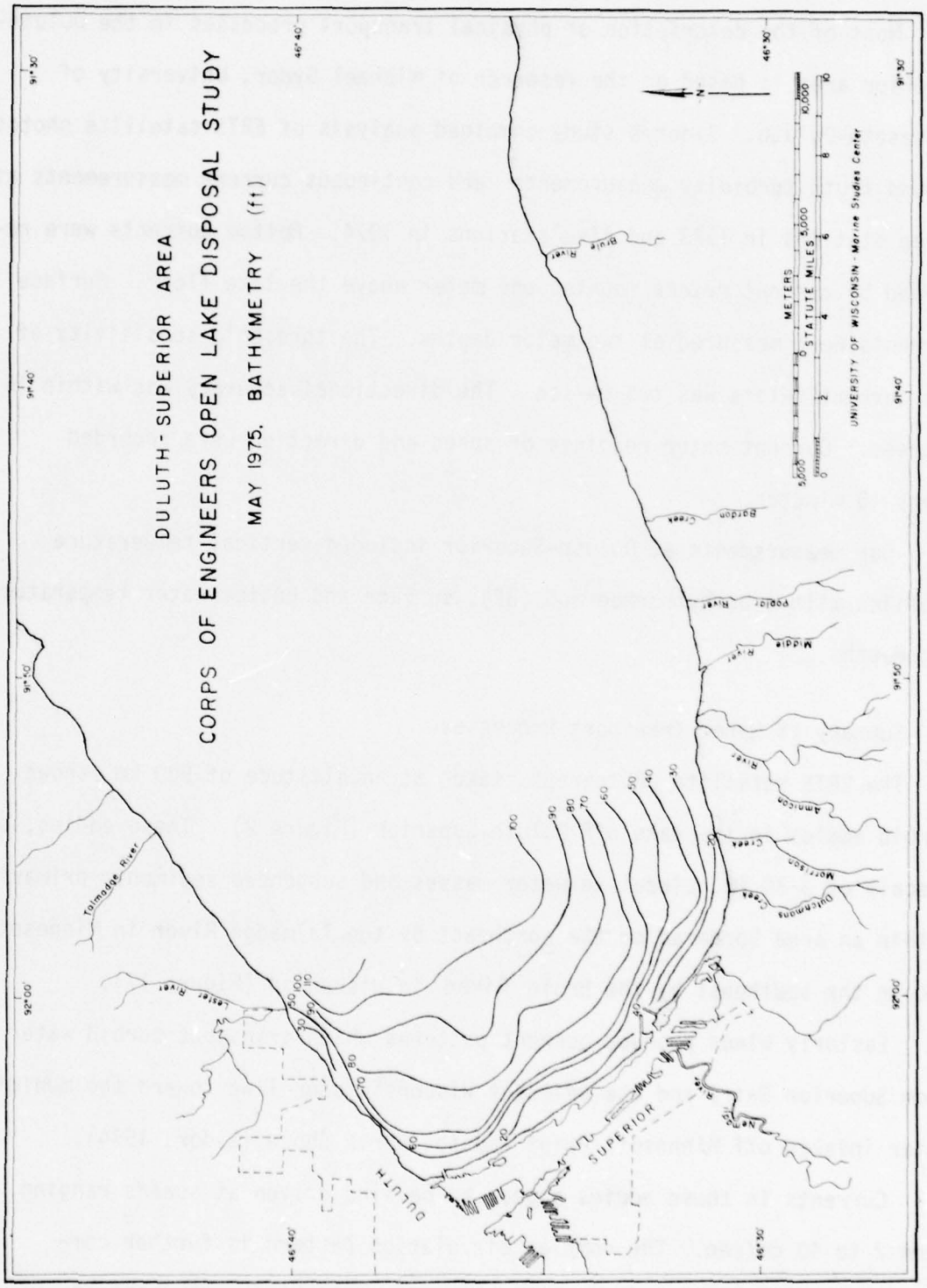
A. Summary of Water Transport Processes

The ERTS satellite photograph taken at an altitude of 900 km shows turbid eddies in the lake off Duluth-Superior (Figure 2). These eddies, on a scale of 3-10 km, circulate water masses and suspended sediments primarily within an area bordered on the northeast by the Talmadge River in Minnesota and on the southeast by the Brule River in Wisconsin (Figure 17).

Easterly winds produce current patterns which transport turbid water from Superior Entry and the adjacent Wisconsin shoreline toward the municipal water intakes off Minnesota Point and the North Shore (Sydor, 1974).

Currents in these eddies appear to be wind driven at speeds ranging from 2 to 40 cm/sec. The complex circulation pattern is further complicated during periods of thermal stratification by the movement of bottom currents in directions other than those of the surface currents.

70 (Figure 17)


DULUTH - SUPERIOR AREA
CORPS OF ENGINEERS OPEN LAKE DISPOSAL STUDY
MAY 1975, BATHYMETRY (ft)
UNIVERSITY OF WISCONSIN - Marine Studies Center
METERS
STATUTE MILES
Blue River
Bardon Creek
Poplar River
Middle River
Amnicon River
Dutchmans Creek
Morrison Creek
Tolmadge River
Lester River
DULUTH
SUPERIOR
92°00'
91°50'
91°40'
91°30'
46°40'
46°30'

Thermal stratification in the Duluth-Superior area begins with the spring warming of surface waters and becomes pronounced in mid-June. Surface water temperatures approach 20°C in late summer. By mid-November, the lake is nearly isothermal.

Bottom water temperatures in shallow water can change rapidly for short periods in the summer and early fall due to vertical mixing caused by storm waves. Upwelling of bottom water occurs along the North Shore when westerly winds move surface waters offshore. Winds from the east have the opposite effect--driving surface water to depths of 24 m or more along the North Shore.

Wave action moves sediment predominantly west along Wisconsin Point and mainly southeast along Minnesota Point--building or eroding the beaches with the sand suspended in the littoral drift. Occasionally, storms are accompanied by strong northeasterly winds blowing over 478 km of open water and causing high waves in the area. These waves erode the shoreline and re-suspend fine bottom sediments in the water column.

Heavy precipitation also causes turbidity offshore as rain-swollen rivers discharge silt and clay into the lake. Turbid plumes occasionally extend long distances along the Wisconsin coast--sometimes as far as Bark Point and Cornucopia, 70 km east of the Superior Entry (Figure 2).

B. Winds

Figures 18 through 21 show monthly and annual distribution of winds at the Duluth airport for a ten year period: 1951-1960. These data provide a climatological description of wind patterns, not a summary of actual lake winds. The Duluth airport is located over 250 m above the level of the lake and about 10 km northwest of the lake. Airport winds

may be representative of lake winds when major storm systems are present, but during periods of light wind, conditions on the lake are probably considerably different from those at the airport. Winds from the east northeast have the most effect on wave action at Duluth since the over water distance (fetch) is approximately 478 km from Superior Entry to Heron Bay, Ontario.

Characteristically in the summer there are frequent winds from the east. They are strongest and most common in May (17% occurrence) and decrease in frequency through the month of July (Figure 18).

The early fall months experience a slight increase in average speed for all directions as compared to July, but frequency distributions of wind direction remain about the same (Figure 19). In the late fall, the air temperature over the lake may be as much as 11^{o} C less than the lake water temperature. The presence of this relatively warm water mass causes a localized increase in the atmospheric pressure gradient, resulting in stronger winds from the west and northwest (U.S. Department of Commerce, 1963). The frequency of easterly winds in November and December declines while the frequency of northwesterly winds increases. November has the highest average wind speeds of the fall and winter months for winds from the east northeast, which occur only six percent of the time.

From January to April, easterly winds become more frequent and westerly winds become less frequent (Figure 20). The frequency distribution of the dominant northwesterly wind is almost identical in January and February, and then it declines in March and April with the shift towards winds from the east. Average speeds of easterly winds increase from January to April.

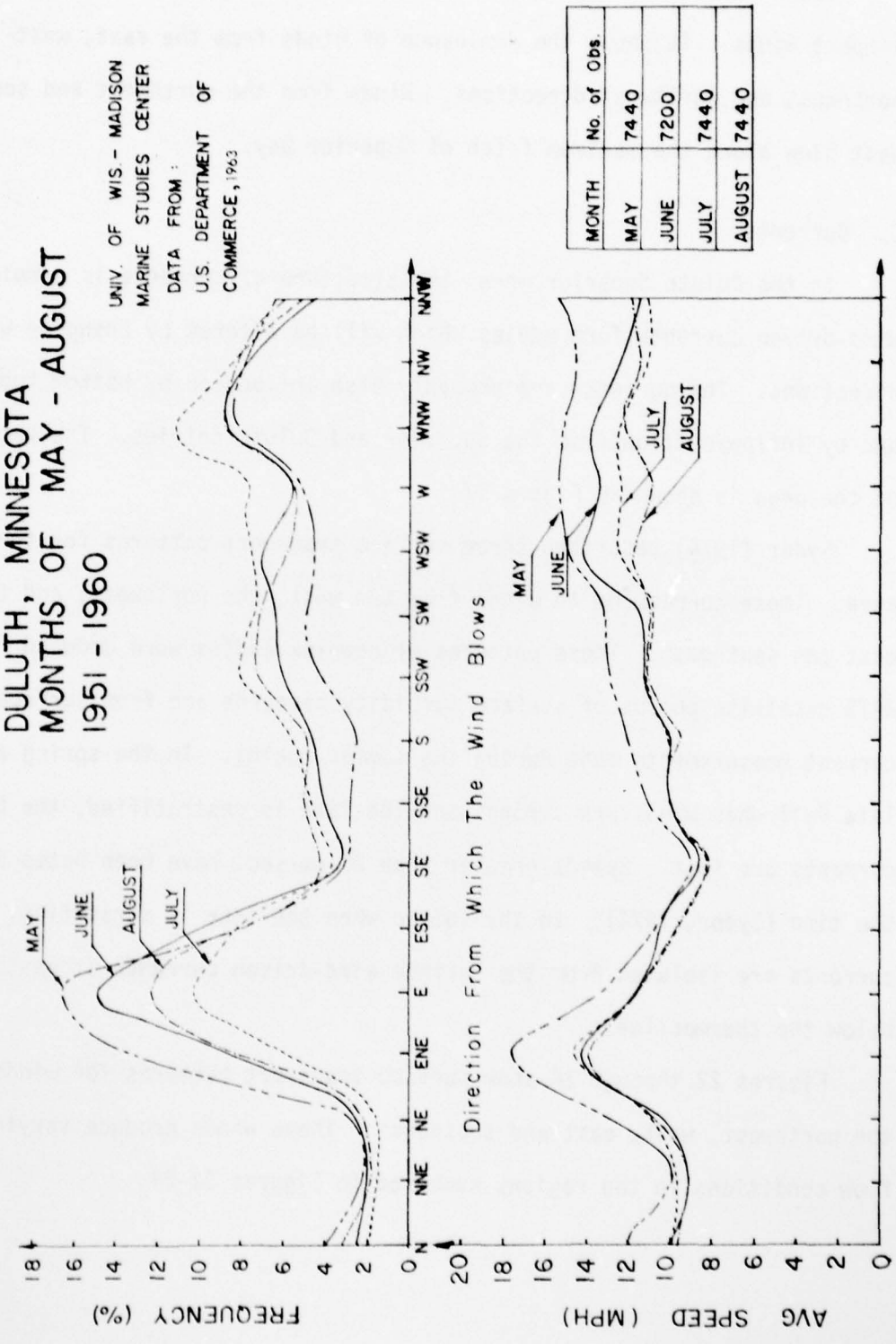
The wind rose in Figure 21 provides an annual summary of Duluth airport winds. It shows the dominance of winds from the east, west-northwest and northwest directions. Winds from the northwest and southeast blow along the maximum fetch of Superior Bay.

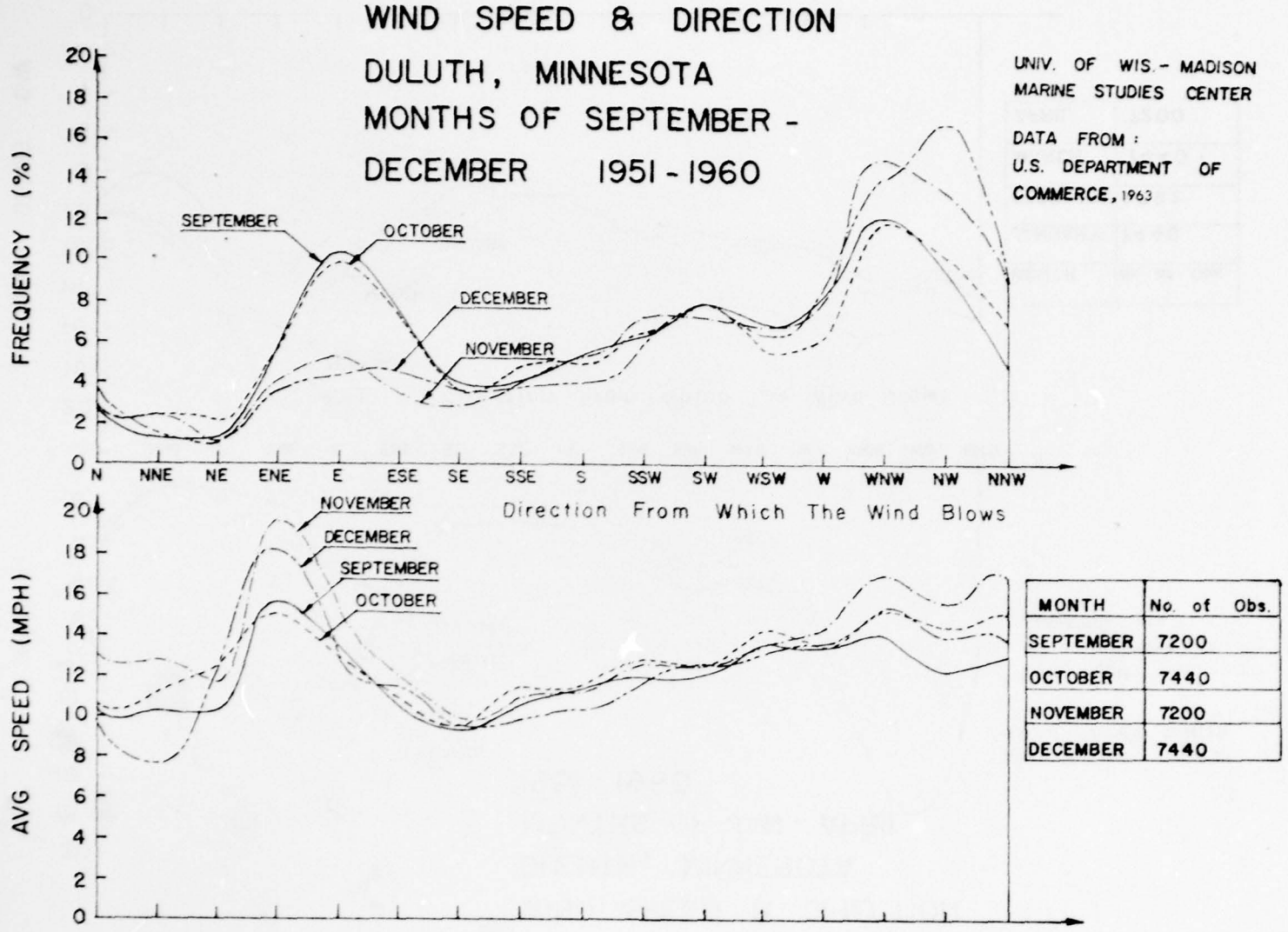
C. Currents

In the Duluth-Superior area, the structure of currents is complex. Wind-driven currents form eddies which will be altered by changing wind directions. The currents are probably also influenced by bottom topography and by inflow/outflow from the Superior and Duluth Entries. The bathymetry of the area is shown in Figure 17.

Sydor (1974) describes three surface transport patterns for the area. These correspond to winds from the west, the northwest, and the east and southeast. These patterns of complex eddies were deduced from ERTS satellite photos of surface turbidity patterns and from surface current measurements made during the summer months. In the spring and late fall when winds are strong, and the lake is unstratified, the bottom currents are fast. Speeds greater than 20 cm/sec. have been noted 5% of the time (Sydor, 1974). In the summer when the lake is stratified, bottom currents are isolated from the surface wind-driven currents at depths below the thermocline.

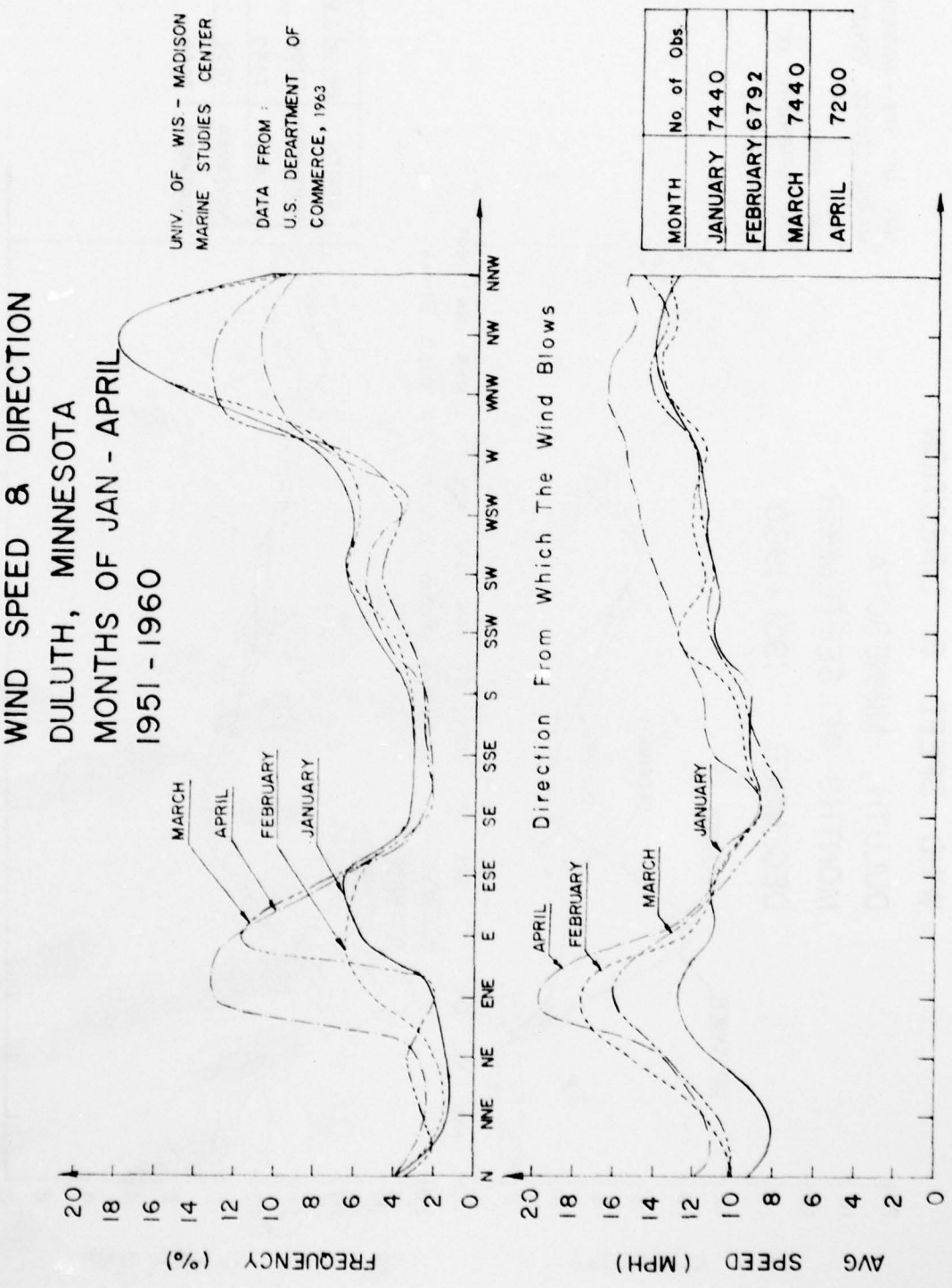
Figures 22 through 24 show surface transport patterns for winds from the northwest, west, east and southeast. These winds produce varying flow conditions in the regions numbered in Figures 22-24.

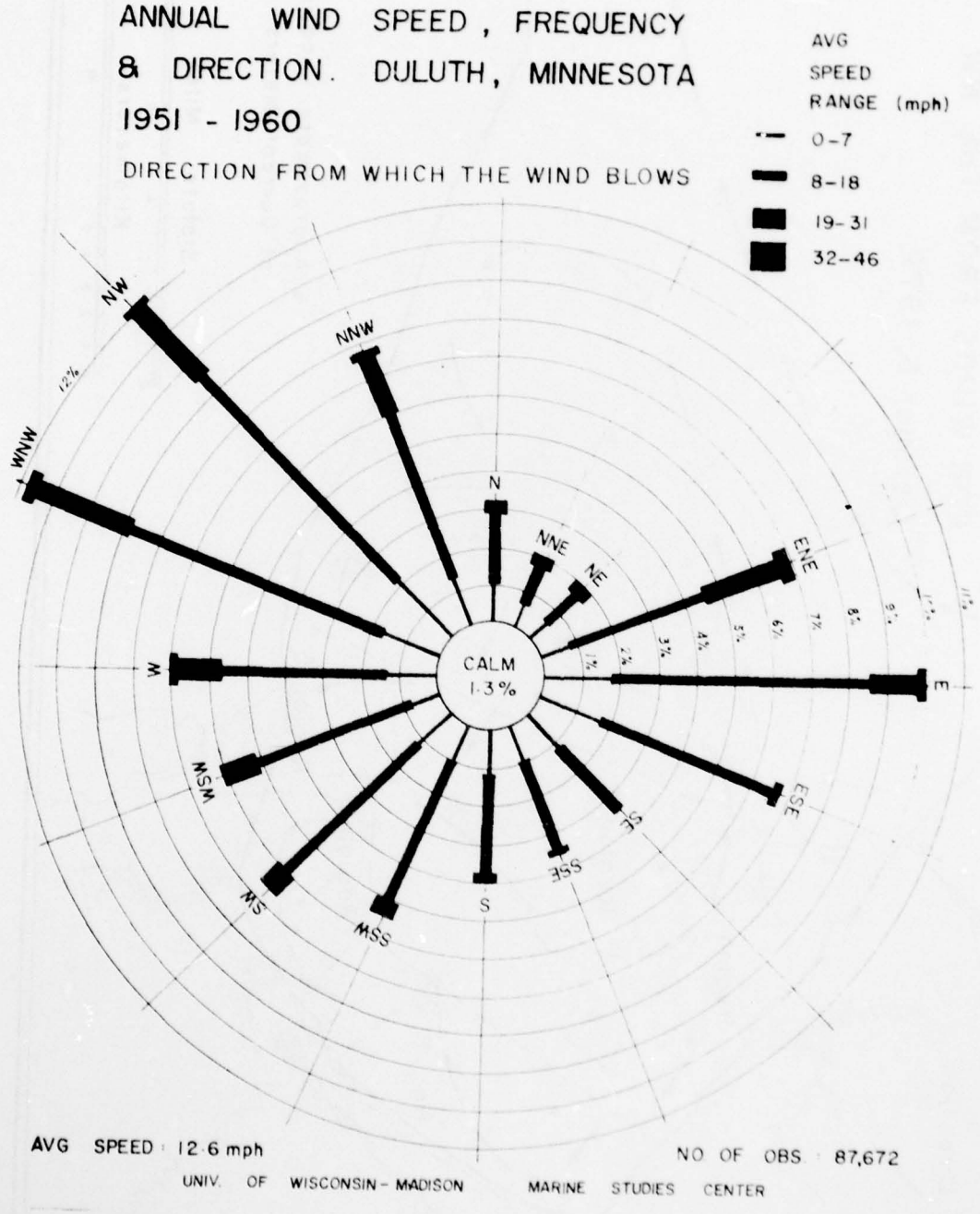

WIND SPEED & DIRECTION
DULUTH, MINNESOTA
MONTHS OF MAY - AUGUST
1951 - 1960
UNIV. OF WIS - MADISON
MARINE STUDIES CENTER
DATA FROM:
U.S. DEPARTMENT OF COMMERCE, 1963
MONTH | No. of Obs.
MAY | 7440
JUNE | 7200
JULY | 7440
AUGUST | 7440
FREQUENCY (%)
AVG SPEED (MPH)
Direction From Which The Wind Blows
N NNE NE ENE E ESE SE SSE S SSW SW WSW W WNW NW NNW
MAY
JUNE
JULY
AUGUST


WIND SPEED & DIRECTION
DULUTH, MINNESOTA
MONTHS OF SEPTEMBER - DECEMBER 1951 - 1960
UNIV. OF WIS. - MADISON
MARINE STUDIES CENTER
DATA FROM :
U.S. DEPARTMENT OF COMMERCE, 1963
FREQUENCY (%)
SEPTEMBER
OCTOBER
DECEMBER
NOVEMBER
N NNE NE ENE E ESE SE SSE S SSW SW WSW W WNW NW NNW
Direction From Which The Wind Blows
AVG SPEED (MPH)
NOVEMBER
DECEMBER
SEPTEMBER
OCTOBER
MONTH | No. of Obs.
SEPTEMBER | 7200
OCTOBER | 7440
NOVEMBER | 7200
DECEMBER | 7440

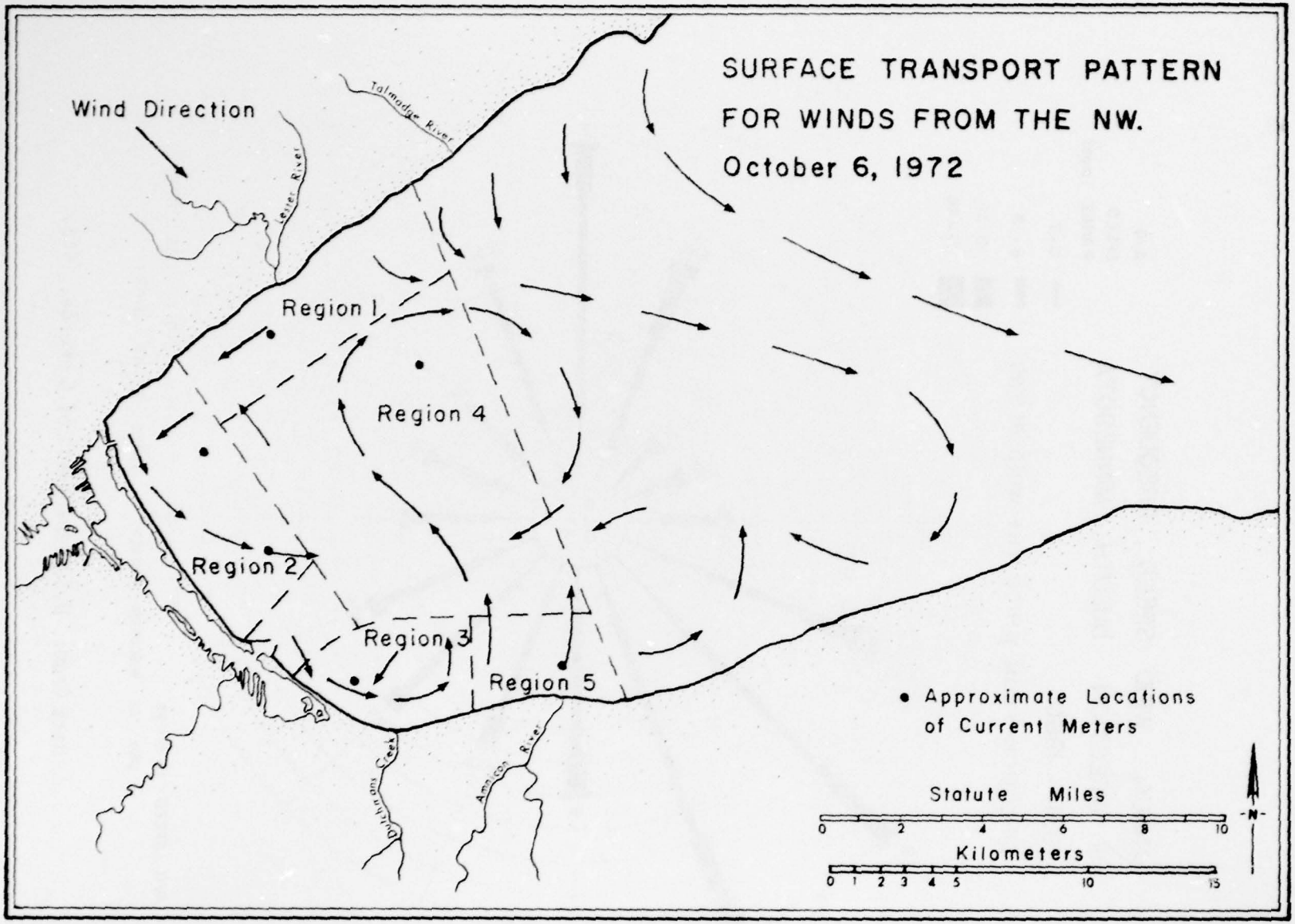
(Figure 19)

(Figure 20)


WIND SPEED & DIRECTION
DULUTH, MINNESOTA
MONTHS OF JAN - APRIL
1951 - 1960
UNIV. OF WIS - MADISON
MARINE STUDIES CENTER
DATA FROM :
U.S. DEPARTMENT OF
COMMERCE, 1963
MARCH
APRIL
FEBRUARY
JANUARY
FREQUENCY (%)
Direction From Which The Wind Blows
AVG SPEED (MPH)
N NNE NE ENE E ESE SE SSE S SSW SW WSW W WNW NW NNW
0 2 4 6 8 10 12 14 16 18 20
MONTH | No of Obs
JANUARY | 7440
FEBRUARY | 6792
MARCH | 7440
APRIL | 7200

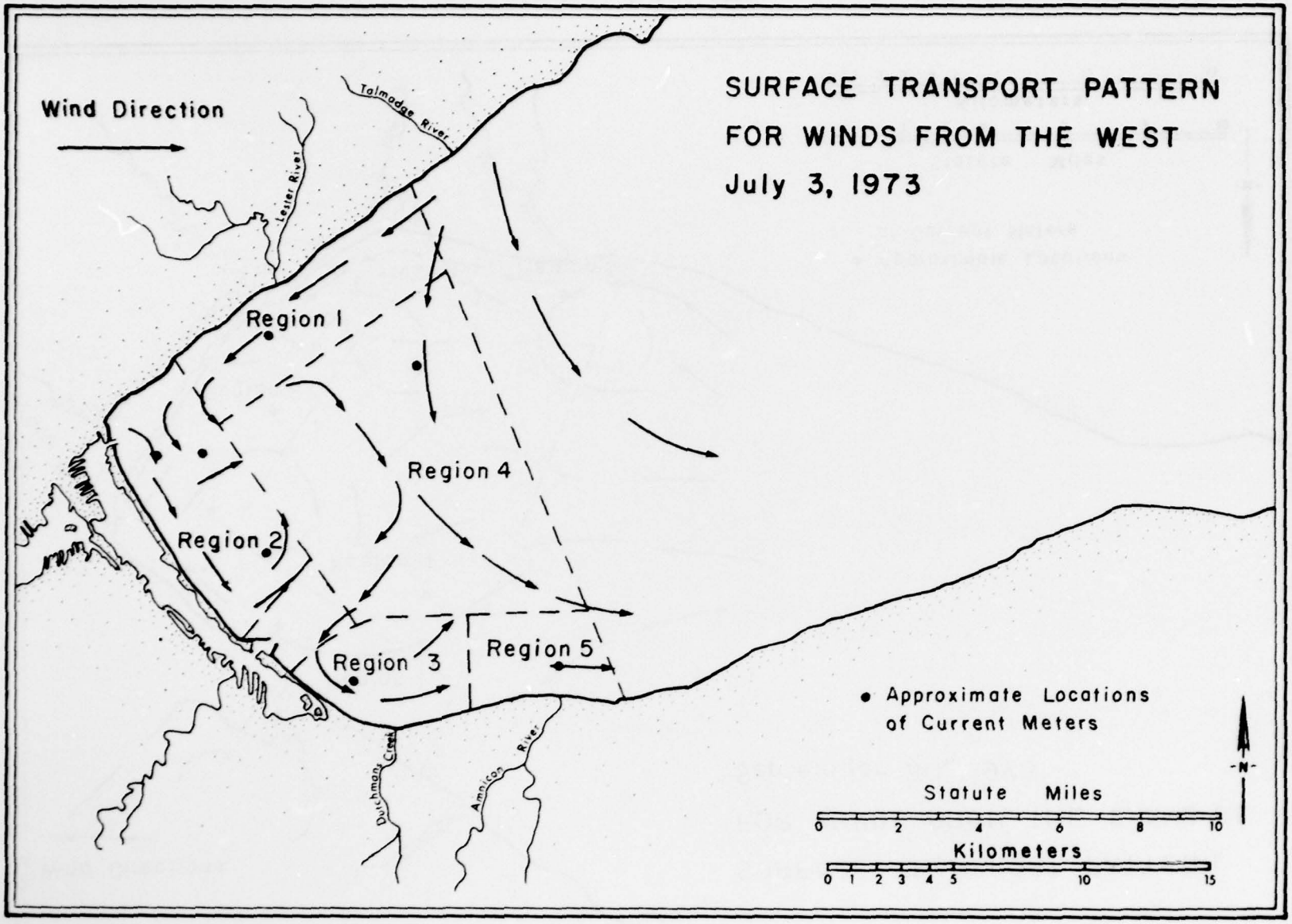


Data From: U.S. Department of Commerce, 1963.



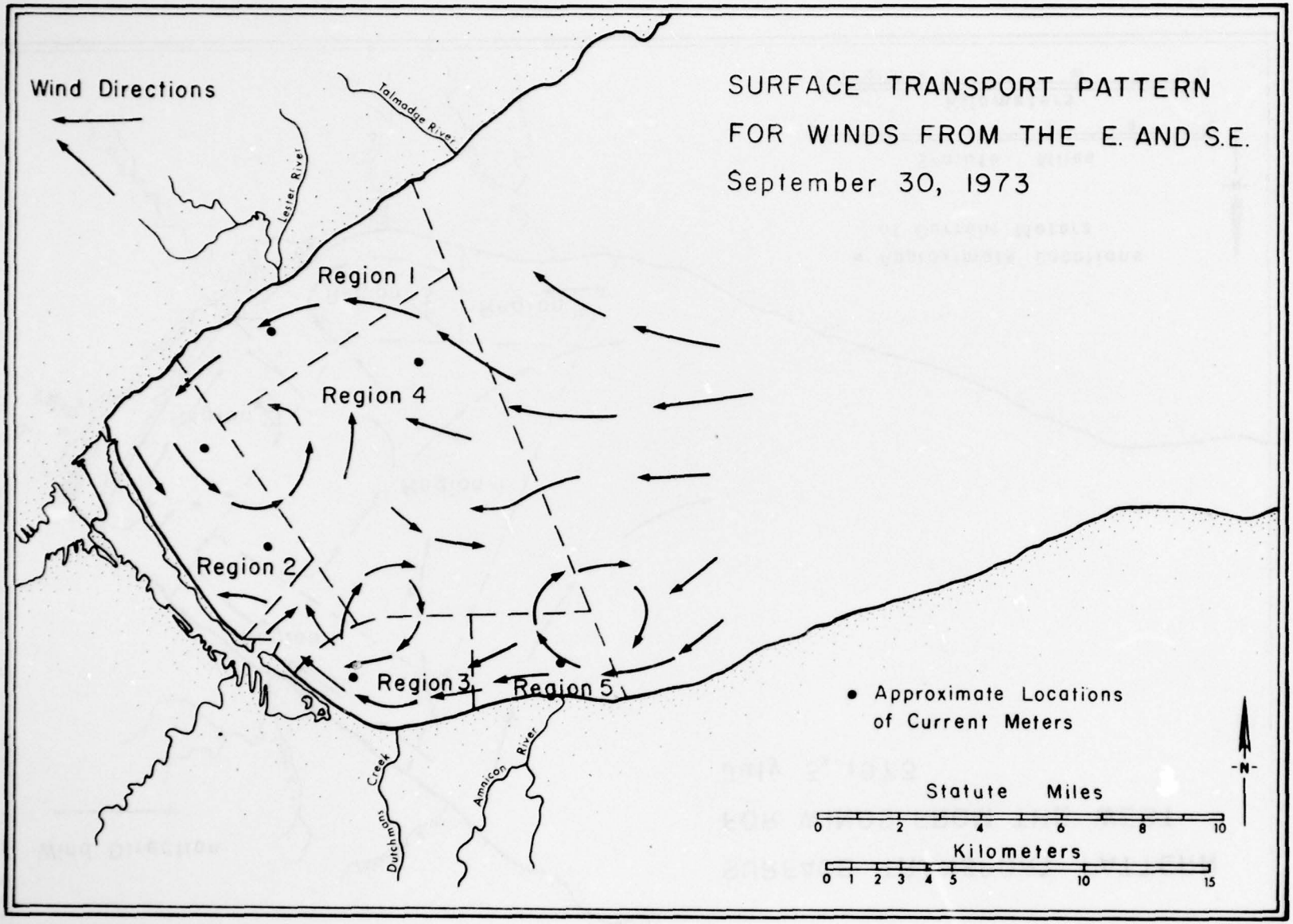
Source: Sydor, 1974

(Figure 22)



Source: Sydor, 1974

(Figure 23) 79



(Figure 24)

Source: Sydor, 1974

1. Region 1 - North Shore Area

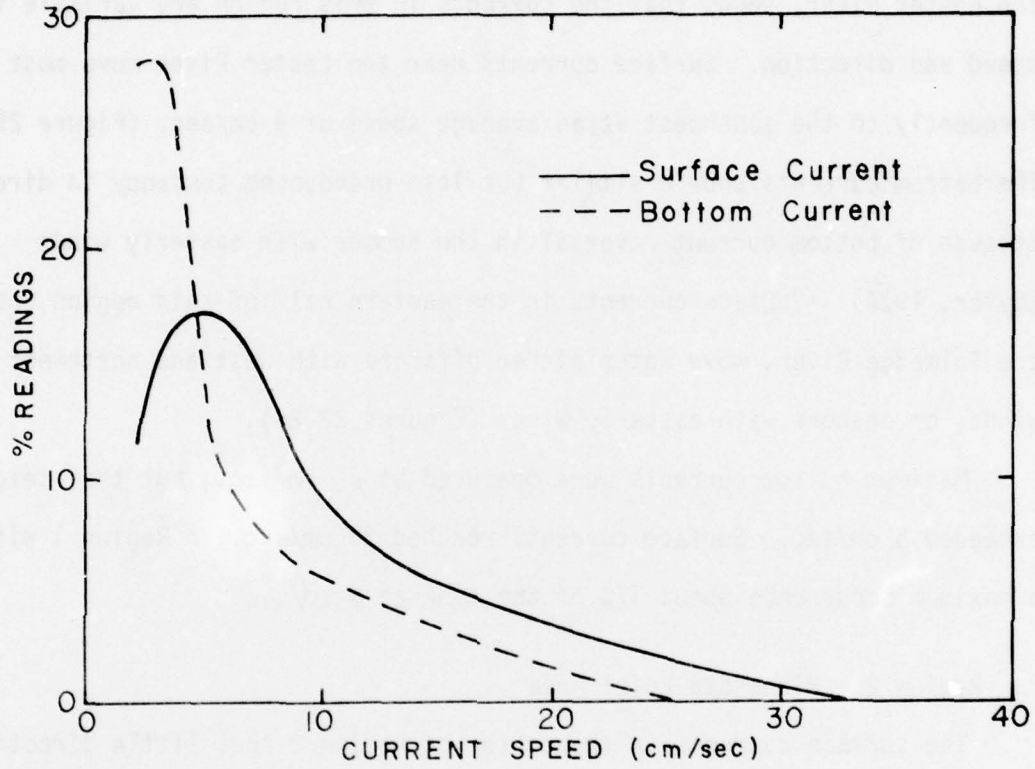
Current meter data from the western half of the North Shore, near the Lester River, shows that the currents in this region are variable in speed and direction. Surface currents near the Lester River move most frequently to the southwest at an average speed of 9 cm/sec. (Figure 25). The bottom currents show a similar but less pronounced tendency in direction because of bottom current reversal in the summer with easterly winds (Sydor, 1974). Surface currents in the eastern half of this region, near the Talmadge River, move water either offshore with west and northwest winds, or onshore with easterly winds (Figures 22-24).

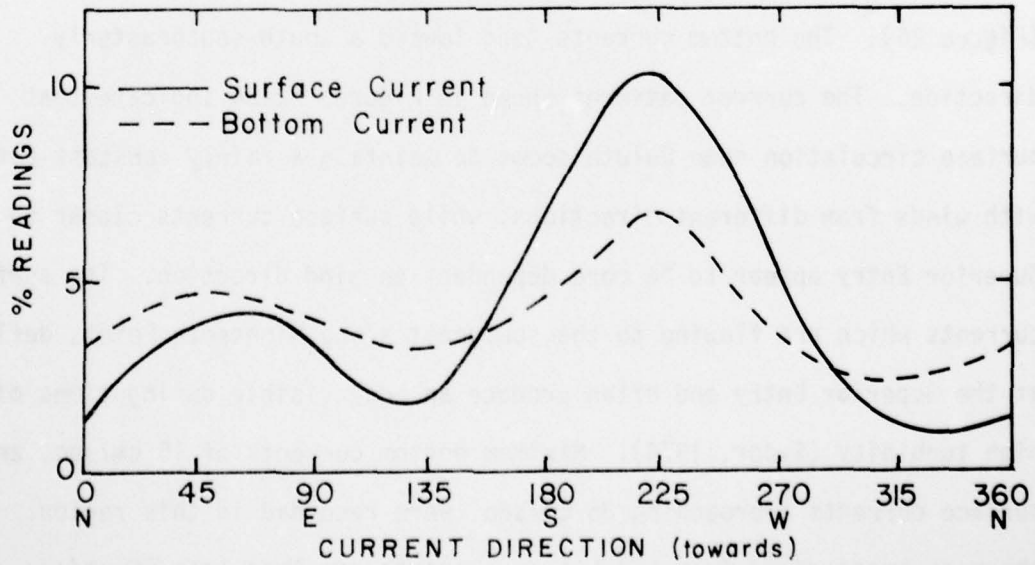
Maximum bottom currents were measured at 25 cm/sec., but they seldom exceeded 5 cm/sec. Surface currents reached 35 cm/sec. in Region 1 with a maximum occurrence about 17% of the time at 5 cm/sec.

2. Region 2 - Minnesota Point Area

The surface currents in the center of Region 2 show little directional preference because of the presence of the eddy in this area (Sydor, 1974) (Figure 26). The bottom currents tend toward a south southeasterly direction. The current patterns shown in Figures 22-24 indicate that surface circulation near Duluth seems to maintain a fairly constant pattern with winds from different directions, while surface currents closer to Superior Entry appear to be more dependent on wind direction. The surface currents which are flowing to the southeast along Minnesota Point, deflect at the Superior Entry and often produce an eddy visible during times of high turbidity (Sydor, 1974). Maximum bottom currents of 15 cm/sec. and surface currents approaching 35 cm/sec. were recorded in this region. However, the mean speed of surface and bottom currents was less than 10 cm/sec.

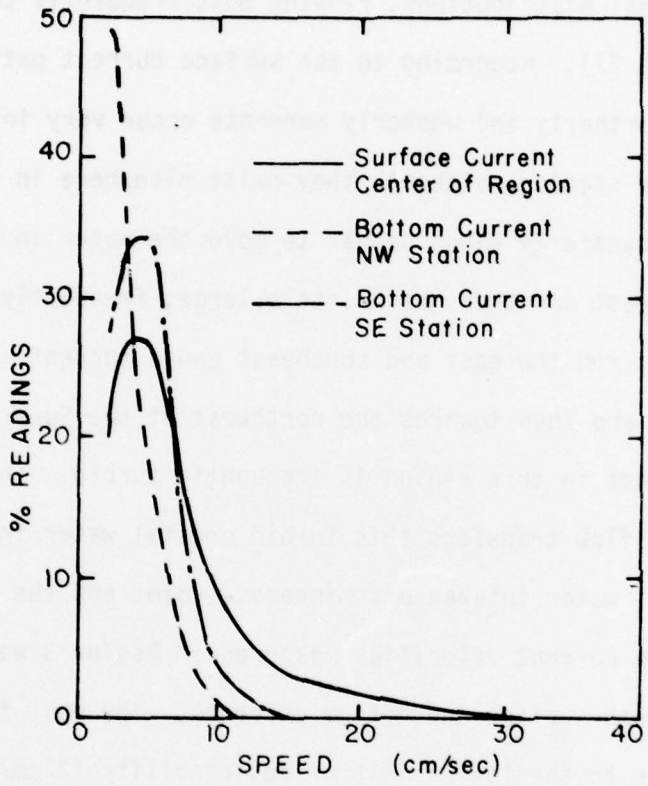
DISTRIBUTION OF CURRENTS NEAR THE NORTH SHORE - REGION I VICINITY OF THE LESTER RIVER

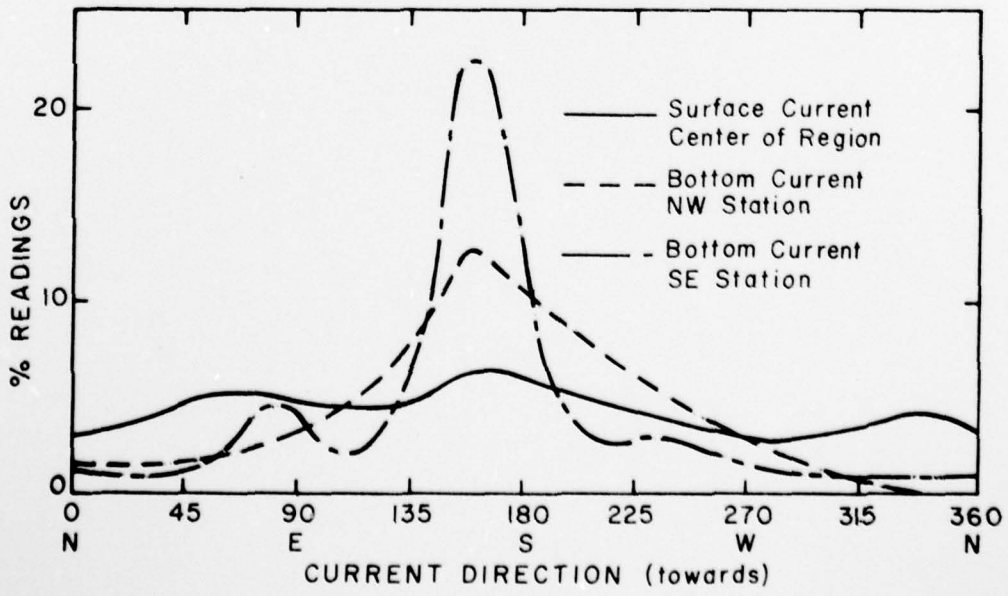




Source: Sydor, 1974

DISTRIBUTION OF CURRENTS OFF MINNESOTA POINT - REGION 2



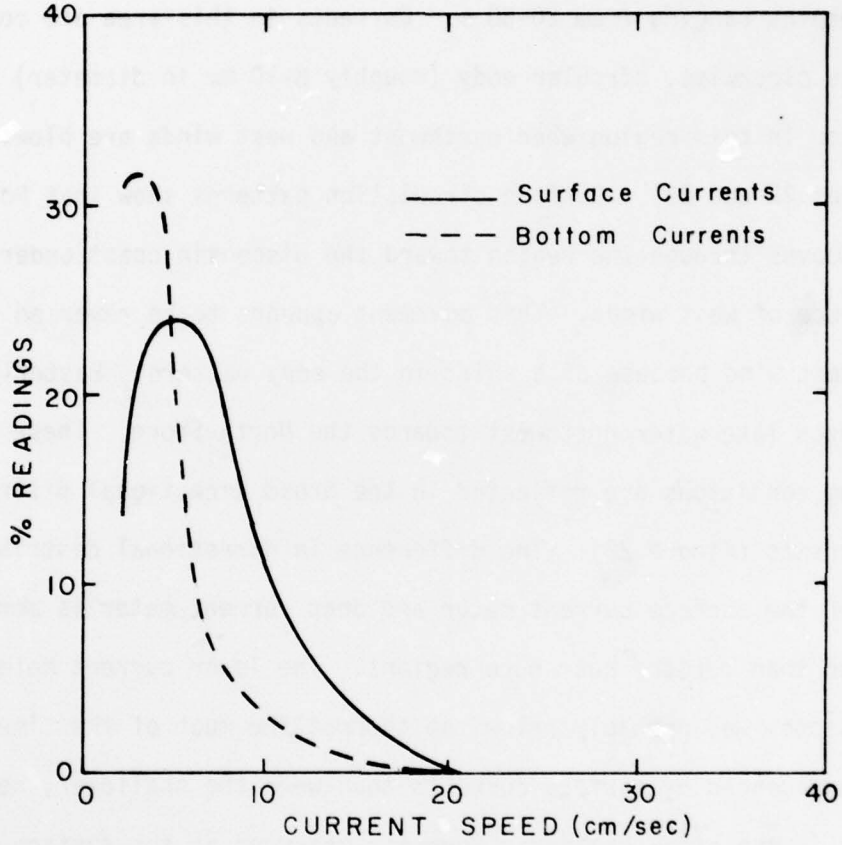


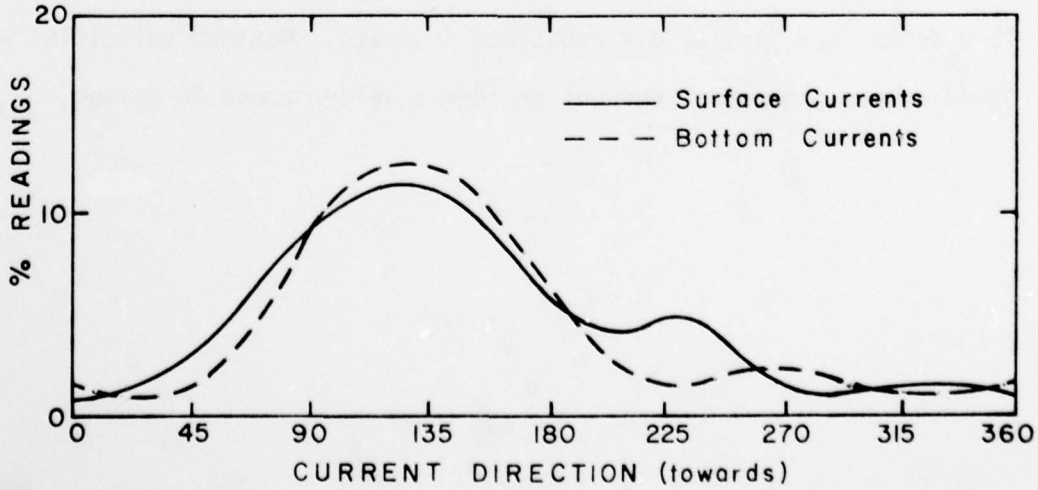
Source: Sydor, 1974

3. Region 3 - Dutchman's Creek Area

Bottom and surface currents in the Dutchman's Creek area have similar directional distributions, flowing most frequently towards the southeast (Figure 27). According to the surface current patterns of Figures 22-24, northerly and westerly currents occur very infrequently at this nearshore station, although they exist elsewhere in the region. In general, northwesterly winds appear to move the water in this region toward the southeast and then north into a large, frequently turbid eddy offshore. Winds from the east and southeast cause currents flowing towards the west and then towards the northwest at the Superior Entry. The Wisconsin coast in this region is frequently turbid. The northerly, offshore current flow transfers this turbid coastal water into deeper areas towards municipal water intakes off Minnesota Point and the Minnesota north shore. The current velocities measured in Region 3 were below 20 cm/sec. for both surface and bottom currents. The most frequent speeds were close to the lower limit of detectability (2 cm/sec.).

DISTRIBUTION OF CURRENTS OFF DUTCHMAN'S CREEK - REGION 3



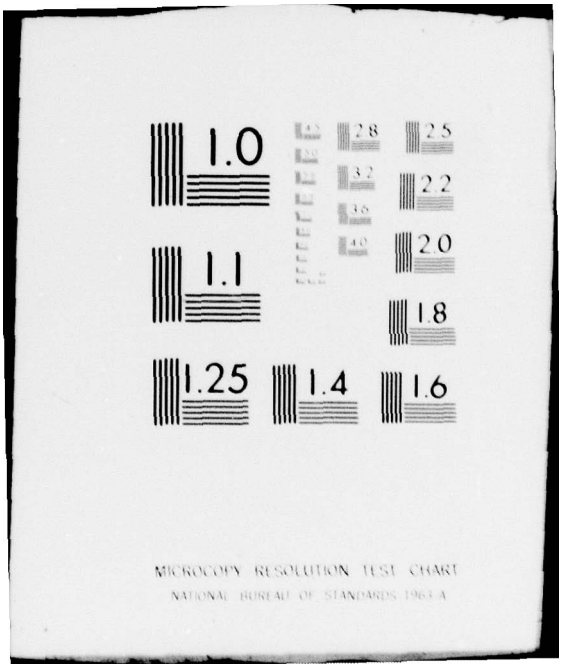


Source: Sydor, 1974

AD-A073 267 WISCONSIN UNIV-MADISON MARINE STUDIES CENTER F/G 13/2
AN ASSESSMENT OF THE ENVIRONMENTAL EFFECTS OF DREDGED MATERIAL --ETC(U)
MAR 76 J P KEILLOR, J YOUNG, R A RAGOTZKIE DACW37-74-C-0013
UNCLASSIFIED NL

2 OF 2
AD A073267

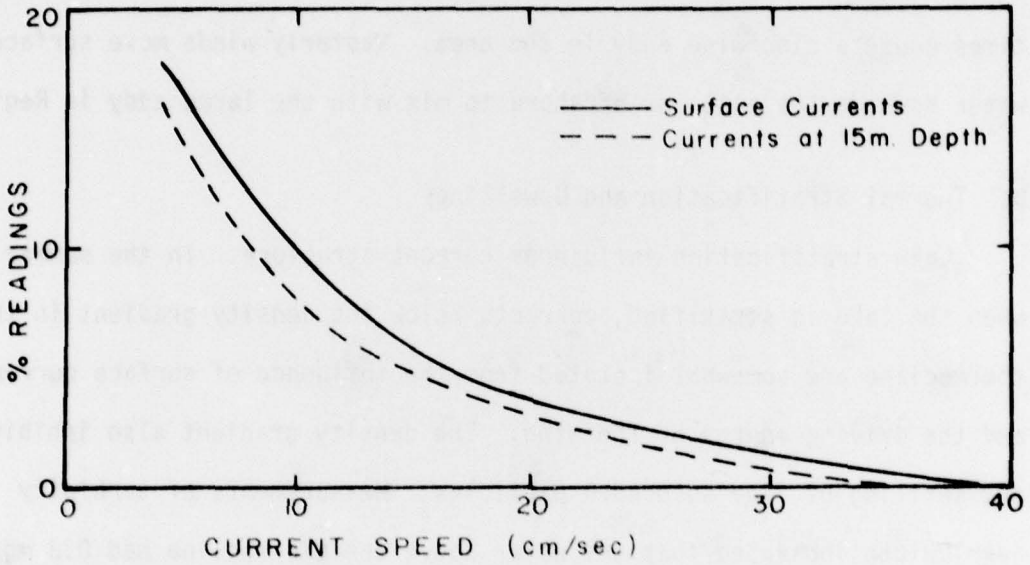
END
DATE FILMED
9-79
DDC

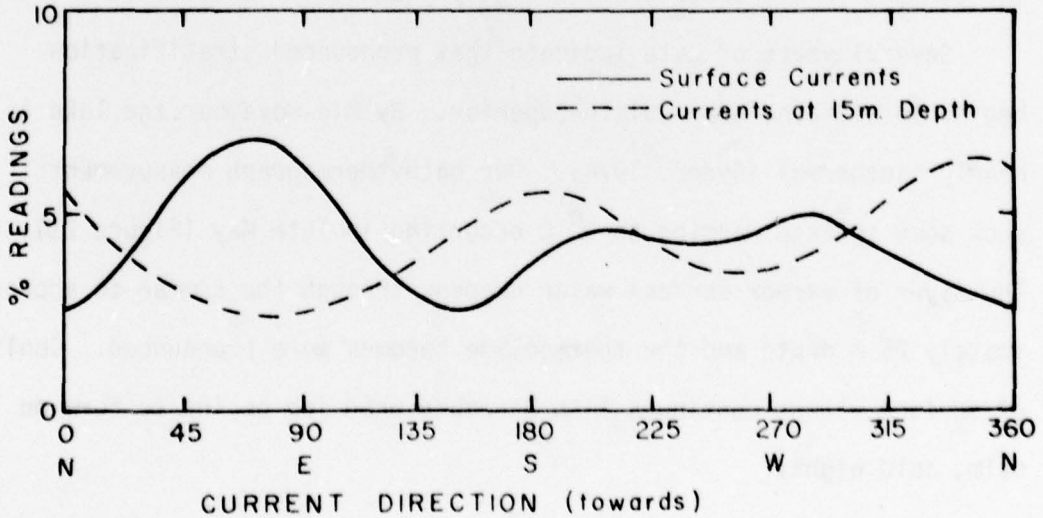

1.0
1.1
1.25
1.4
1.6
2.8
3.2
3.6
4.0
2.5
2.2
2.0
1.8
MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963-A

4. Region 4

Region 4 is a large area 5-14 km northeast of Minnesota Point, with depths ranging from 20-50 m. Currents in this area are complex. A large clockwise, circular eddy (roughly 8-10 km in diameter) has been observed in this region when northwest and west winds are blowing (Figures 22 and 23). Surface circulation patterns show that North Shore Water moves through the region toward the Wisconsin coast under the influence of west winds. This movement appears to be reversed with a northwest wind because of a shift in the eddy pattern. Easterly winds move open lake water northwest towards the North Shore. These widely varying conditions are reflected in the broad directional distribution of currents (Figure 28). The difference in directional distribution between the surface current meter and deep current meter is more pronounced than for the nearshore regions. The lower current meter, at 15 m depth, was probably below the thermocline much of the time and was less influenced by surface currents than were the shallower, nearshore meters in the other Regions. Currents measured at the surface and at 15 m depth show similar distributions in speed. Maximum velocities were 35-40 cm/sec., however, current speed was seldom above 20 cm/sec.

CURRENT DISTRIBUTION - REGION 4





Source: Sydor, 1974

5. Region 5 - Amnicon River Area

Region 5 is an area 8-13 km east of Superior Entry, off the Amnicon River. This area often has a band of turbid water along the Wisconsin coast. The average current seems to flow towards the east at speeds of 12 cm/sec. (Sydor, 1974). Winds from the east and southeast sometimes cause a clockwise eddy in the area. Westerly winds move surface water towards the east, or offshore to mix with the large eddy in Region 4.

D. Thermal Stratification and Upwelling

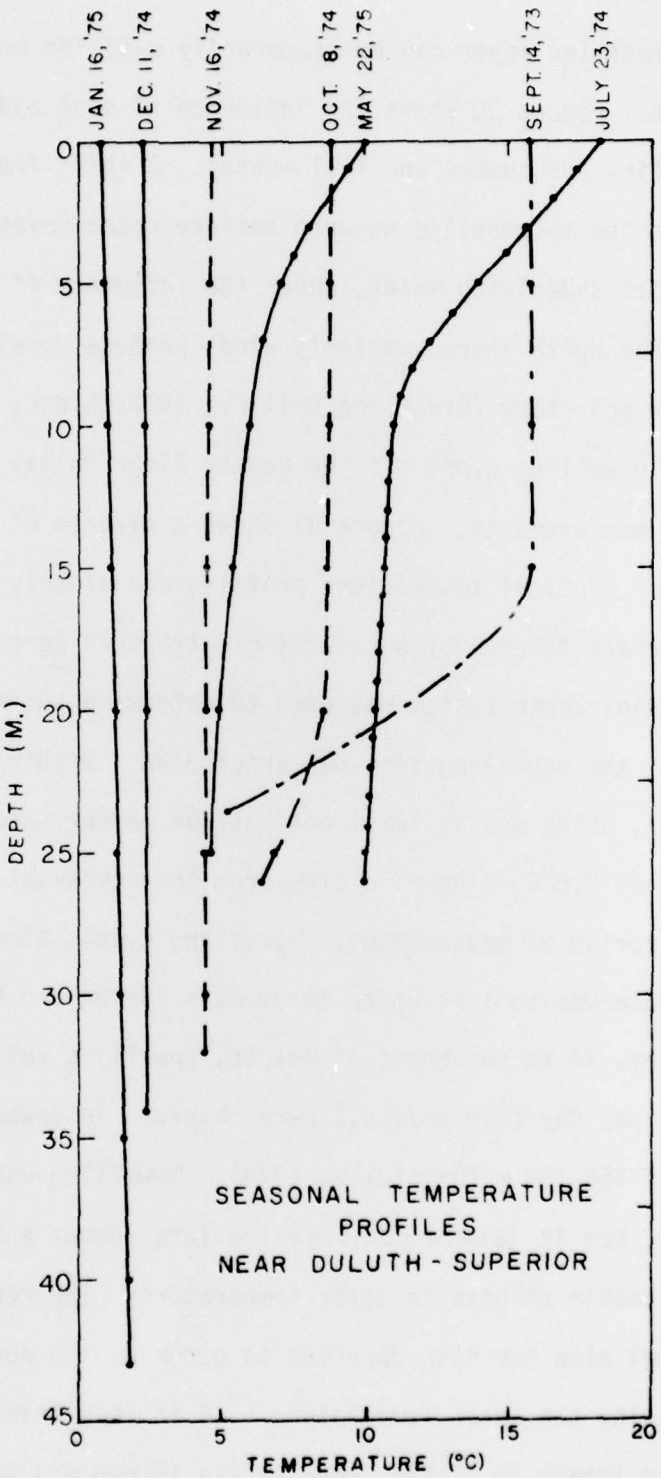
Lake stratification influences current structure. In the summer, when the lake is stratified, currents below the density gradient in the thermocline are somewhat isolated from the influence of surface currents, and the driving energy of the wind. The density gradient also inhibits the settling of fine suspended particles. Measurements of turbidity near Duluth indicated that the water above the thermocline had 0.3 mg/liter more suspended solids than the water below the thermocline (averaged over the summer, in the absence of turbidity plumes) (Sydor, 1974).

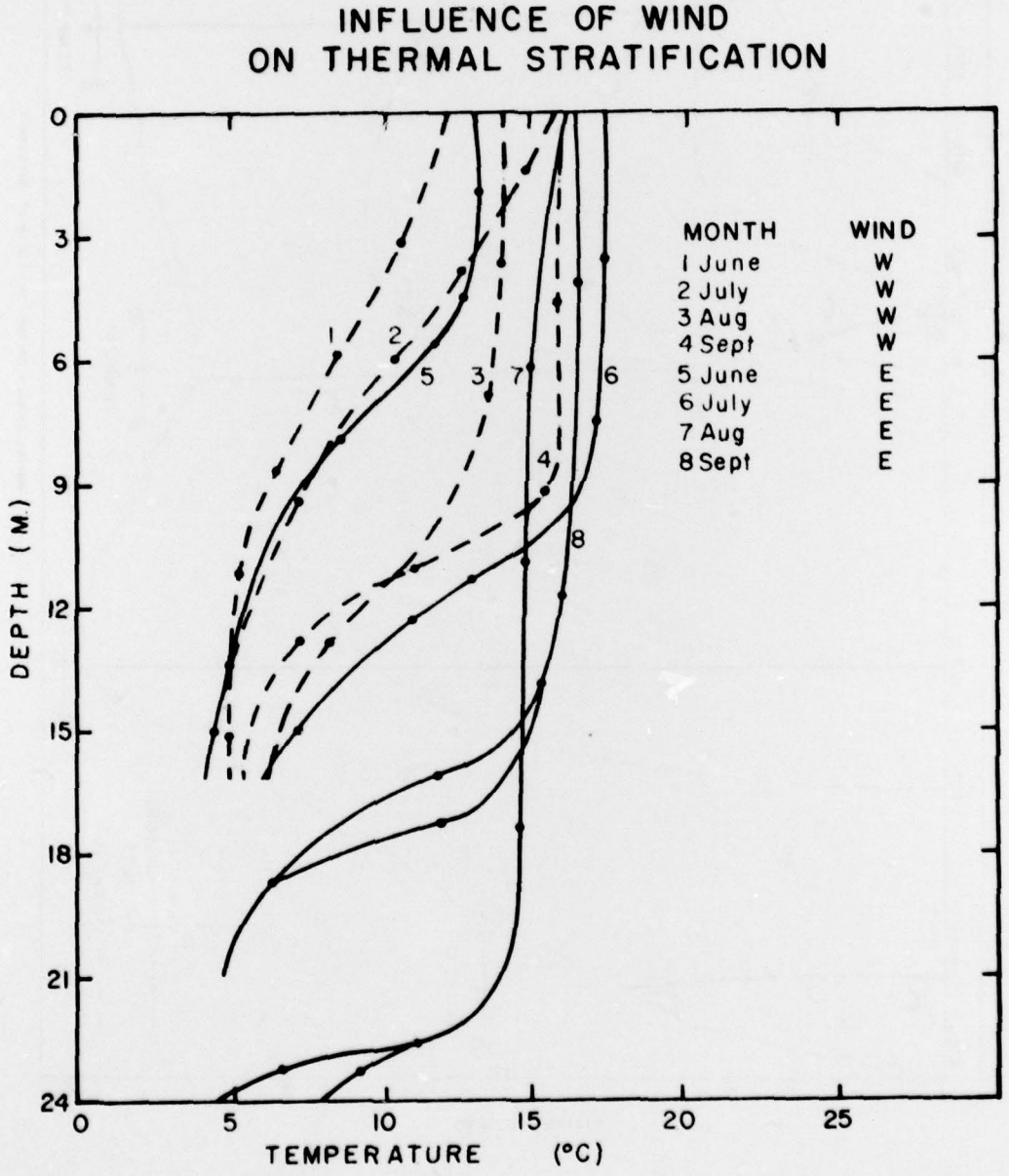
Several years of data indicate that pronounced stratification begins in mid-June near Duluth-Superior. By mid-November the lake is nearly isothermal (Sydor, 1974). Our bathythermograph measurements show some surface warming to 9^{o} C occurring in late May (Figure 29). The layer of warmer surface water deepens through the summer to approximately 25 m depth and the thermocline becomes more pronounced. Cooling of surface waters continues into December when ice begins to form on calm, cold nights.

The stratified layer can be temporarily modified or destroyed by strong winds. Figure 30 shows the influence of east and west winds on the thermocline for summer and fall months. A shift from west to east winds lowers the thermocline as warm surface water moves into the area and mixes with underlying water, under the influence of wind stress.

Along the North Shore, westerly winds produce upwelling of colder bottom water nearshore (Green and Keillor, 1973; Sydor, 1974). We detected an upwelling event off the Lester River on May 26, 1975 and took temperature measurements. Figure 31 shows a diagram of this upwelling based on four vertical temperature profiles and closely spaced measurements of surface temperatures on a single transect perpendicular to shore. A Raytheon Miniranger system was used to determine surface positions. The width of the upwelling zone was about 3 km. Within this zone of 4^{o}-6^{o}C water, there was at least one cell of warmer water with a surface temperature of 9.6^{o}C. The wind blew from the southwest at 26 km/hr. during the period of measurement. Upwelling events along this coast have been observed to last up to three days (Green and Keillor, 1973). At Silver Bay, 84 km northeast of Duluth, upwelling velocities as high as 100 feet per day (.38 cm/sec.) were observed in upward moving water at depths of 150-180 m (Ragotzkie, 1974). Upwelling can occur anytime of the year, but it is more obvious in the late summer and fall because of the noticeable changes in water temperature. The reverse process (downwelling) also has been observed to occur on the north shore at Duluth, raising the water temperature 5^{o} C in less than one day at the Duluth water intake 30 m below the surface (Green and Keillor, 1973).

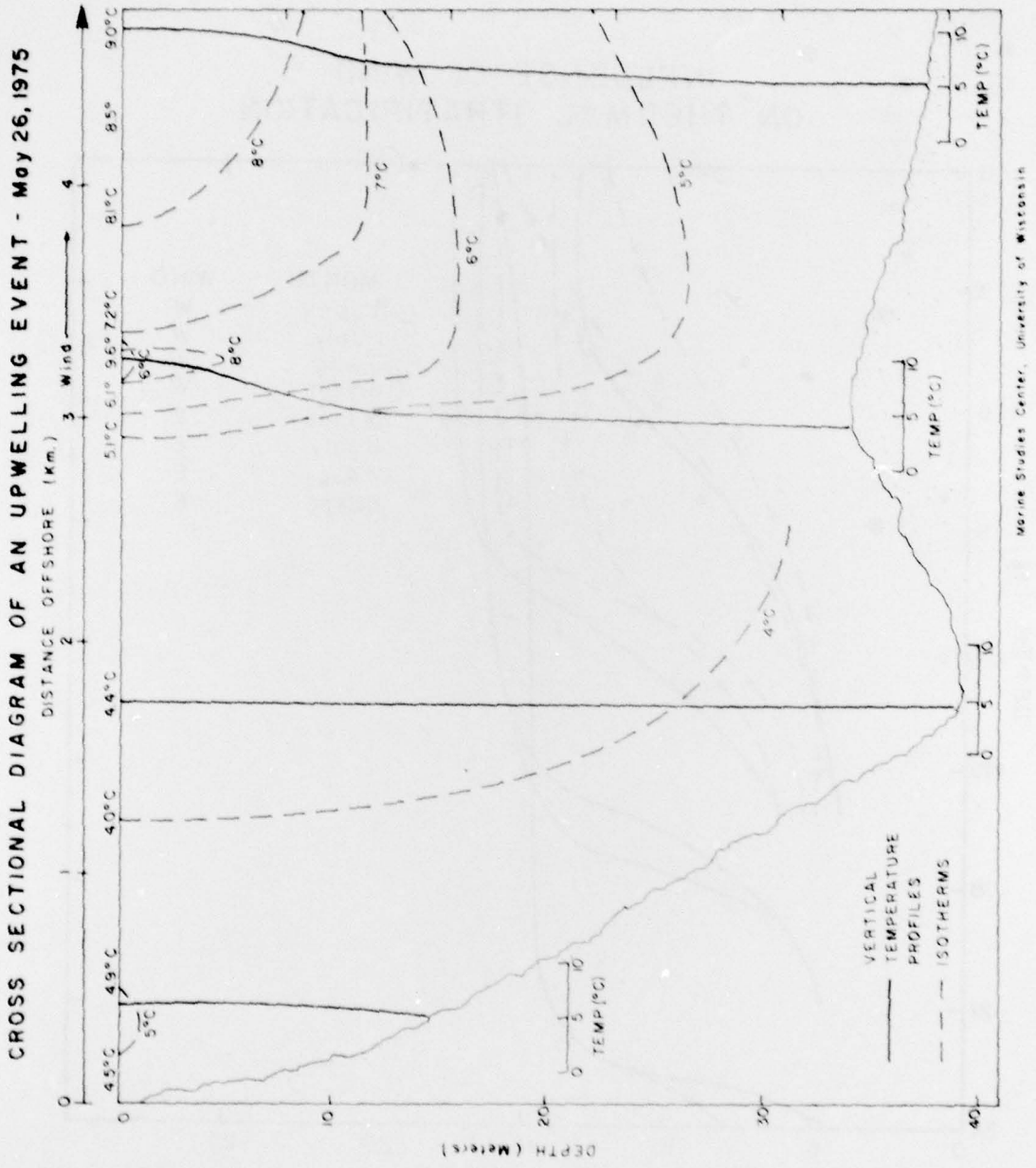
 (Figure 29)


JAN. 16, '75
DEC. 11, '74
NOV. 16, '74
OCT. 8, '74
MAY 22, '75
SEPT. 14, '73
JULY 23, '74
DEPTH (M.)
0
5
10
15
20
25
30
35
40
45
0
5
10
15
20
TEMPERATURE (°C)
SEASONAL TEMPERATURE
PROFILES
NEAR DULUTH - SUPERIOR
Marine Studies Center, University of Wis.



Source: Sydor, 1974

(Figure 31)


CROSS SECTIONAL DIAGRAM OF AN UPWELLING EVENT - May 26, 1975
DISTANCE OFFSHORE (km)
Wind
DEPTH (Meters)
VERTICAL TEMPERATURE PROFILES
ISOTHERMS
TEMP (°C)
Marine Studies Center, University of Wisconsin

E. Wave Action

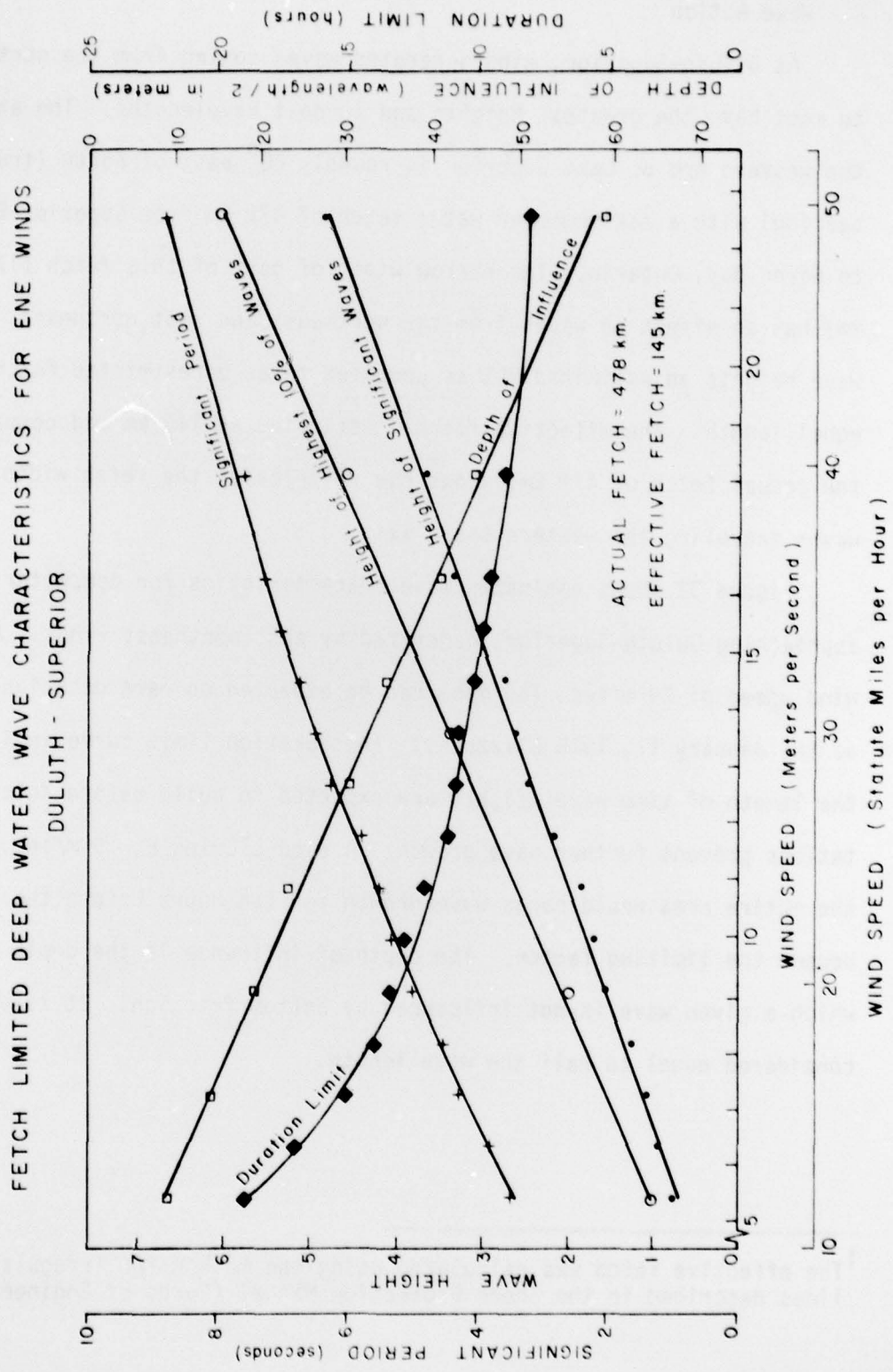
At Duluth-Superior, wind generated waves coming from the northeast to east have the greatest heights and longest wavelengths. The axis of the western arm of Lake Superior is roughly 60° east of north (true bearing) with a maximum over water fetch of 478 km from Superior Entry to Heron Bay, Ontario. The narrow width of part of this fetch (17-240 km) has an effect on waves from the northeast and east northeast, reducing wave heights an estimated 30% as compared to an unrestricted fetch of equal length. The effective fetch[1], estimated at 143 km and compared to the actual fetch of 478 km, shows how restrictive the fetch width is on waves traveling the western basin axis.

Figure 32 shows estimated wave characteristics for deepwater waves approaching Duluth-Superior, generated by east northeast winds. A maximum wind speed of 23 m/sec. (50 mph) can be expected on rare occasions (such as the January 11, 1975 blizzard). The duration limit curve indicates the length of time wave heights are expected to build before fetch limitations prevent further wave growth. A wind blowing at 15 m/sec. over the entire area would cause wave growth for ten hours before the fetch became the limiting factor. The depth of influence is the depth beyond which a given wave is not influenced by bottom friction. It is usually considered equal to half the wave length.

---

[1]The effective fetch was calculated using the method for irregular shorelines described in the Shore Protection Manual (Corps of Engineers, 1973).

(Figure 32)


FETCH LIMITED DEEP WATER WAVE CHARACTERISTICS FOR ENE WINDS
DULUTH - SUPERIOR
SIGNIFICANT PERIOD (seconds)
WAVE HEIGHT
DEPTH OF INFLUENCE (wavelength/2 in meters)
DURATION LIMIT (hours)
Significant Period
Height of Highest 10% of Waves
Height of Significant Waves
Depth of Influence
Duration Limit
ACTUAL FETCH = 478 km.
EFFECTIVE FETCH = 145 km.
WIND SPEED (Meters per Second)
WIND SPEED (Statute Miles per Hour)

March through May is the time of most frequent, strong northeasterly winds in this area. Inspection of 1974 wind records from Thunder Bay and Duluth for these months showed several periods of strong, steady winds at both stations. Using a synthesized[1] over-water wind speed (1.8 times the land wind speed), and simplified wave hindcasting techniques[2], wave estimates for three storms in the spring of 1974 were derived. These are shown in Table 11.

Of the three storms, the storm of March 8, 1974 probably had the highest wave energy. Wave-induced water motion during this event was probably sufficient to move loose medium-size sand particles at depths of 30 m or less[3]. The maximum depth of influence was 38 m.

The calculated significant wave heights from these occasional storms are less than the maximum significant wave height of 11.3 m estimated by Richards and Phillips (1970) for Lake Superior.

Heights of individual waves may be 1.4 times[4] the height of the significant wave. Hindcast estimates of wave characteristics are only rough approximations. Comparisons of significant wave heights determined by hindcasting and by observation show that hindcast wave heights may be 20% lower to 70% higher than observed wave heights (Kinsman, 1965). Shoaling of the deep water storm waves described in Table 11 will cause a reduction in wave height of up to 10% as the waves travel in towards the beach.

---

[1] Method described by Richard and Phillips, 1970.

[2] Shore Protection Manual; Corps of Engineers, 1973.

[3] The relationship between flow velocity and the size of sediment particles re-suspended is described by Allan, 1965.

[4] Fichand (1960), cited by Richards and Phillips (1970).

Table 11. Estimated Deep Water Wave Characteristics at Duluth-Superior for Three Northeast Spring Storms in 1974.

Date	Average Wind Speed (m/sec)	Wind Duration (hours)	Significant Wave Characteristics				Average height of highest 10% of waves (m)
			Height (m)	Period (sec)	Deepwater Wave Length (m)	Depth of Influence (m)	
3/8	16.54	11	3.3	7	76	38	4.3
4/1	14.75	15	3.0	7	76	38	4.0
4/11-12	12.96	33	2.7	6	56	28	3.0

The previous wave estimates indicate a range of possible wave conditions to be considered in reviewing alternative in-lake disposal sites. Rare, severe storms may generate waves of sufficient height and length to disturb sediments and dredge spoil at depths of 60 m. Occasional storms may generate waves sufficient to re-suspend sediments and spoil at depths out to 40 m. Assuming that a sustained wind speed of 20 mph from the northeast is a common occurrence, dredge spoil deposited in depths out to 18 m will probably be frequently disturbed, according to Figure 32.

F. Turbidity

Sediment re-suspended by wave energy may produce turbid conditions in the water column. This turbid water may then be transported to other areas by currents ranging in speed from 2.5 to 40 cm/sec. (Sydor, 1974).

Re-suspension of bottom sediments by wave action forms a significant part of the turbidity in the Duluth-Superior area. Re-suspended solids have an estimated turnover rate of up to 300,000 metric ton per year in this region, and account for about 25% of the clay-size particles (less than 2 microns in diameter) in large turbid plumes (Sydor, 1975). About 60% of the clay-size particles in suspension are due to shore erosion and about 15% of this material comes from local stream run-off. Turbid plumes near Duluth-Superior occur primarily during periods of easterly storm winds and high precipitation. An average of 12 storm-caused plumes can be expected per year with each plume containing 10^4-10^5 metric tons of suspended solids (Sydor, 1975). Sydor's analysis of ERTS imagery shows that the most frequently turbid areas and areas of highest turbidity are generally located along the Wisconsin south shore.

G. Conclusions

The movement of water borne sediments off Duluth-Superior is strongly influenced by wind-generated waves and currents. Predictions of spoil dispersal in this area are limited by a lack of long-term lake wind data and statistical analysis of wind speed, direction and duration, and by the small number of turbidity events available for analysis of surface current patterns by the use of ERTS imagery. The available data presented in the previous sections give a rough picture of the currents, current patterns, wave activity, winds, seasonal changes in vertical temperature profiles and turbidity which occur in the area. On the basis of this information, it appears that in-lake dumping of dredge spoil in deep areas of 40-60 m, before or after stratification, will reduce dispersal of fine material in the spoil during dumping and during periods of wave activity. If dispersal of fine sediments is desired, nearshore deposition in depths of 18 m or less will accomplish this goal. Deposition in the shallow waters along the south shore would increase the likelihood that suspended dredge spoil would be diluted by suspended sediments from coastal erosion and runoff.

VI. BIBLIOGRAPHY

Bibliography

Allen, J.R.L., 1965, A Review of the Origin and Characteristics of Recent Alluvial Sediments, Sedimentology, Vol. 5, p. 89-191.

Basco, David R., Arnold H. Bouma, Wayne A. Dunlap, 1974, Assessment of the Factors Controlling the Long-Term Fate of Dredged Material Deposited in Unconfined Subaqueous Disposal Areas, Texas A & M University, Prepared for the U.S. Army Engineer Waterways Experiment Station, Contract Report D-74-8.

Coastal Engineering Research Center, 1973, Shore Protection Manual, Volume 1, U.S. Army Corps of Engineers.

Chow, Ven Te, 1959, Open Channel Hydraulics, McGraw-Hill Book Company, New York.

Corps of Engineers, 1973, Shore Protection Manual (3 Volumes), U.S. Army Coastal Engineering Research Center.

Corps of Engineers, 1974, Draft Environmental Impact Statement, U.S. Army Corps of Engineers Project, Duluth-Superior Harbor, St. Paul District, U.S. Army Corps of Engineers, St. Paul, March, 1974.

Fee, Everett J., 1969, Digital Computer Programs for Spectral Analysis of Time Series, Special Report No. 6, Center for Great Lakes Studies, University of Wisconsin, Milwaukee.

Great Lakes Commission, 1974, Great Lakes News Letter, Mid-September to October.

Green, T., J.P. Keillor, 1973, Upwelling Along the North Shore of Lake Superior, May, 1973, unpublished report.

Harrington, M., 1895, Currents on the Great Lakes, U.S. Weather Bureau, Washington, D.C.

Hoopes, J.A., R.A. Ragotzkie, San-Lang Lien, N.P. Smith, 1973, Circulation Patterns in Lake Superior, University of Wisconsin, Water Resources Center, Tech. Report 73-04.

Johnson, B.H., 1973, Investigation of Mathematical Models for the Physical Fate Prediction of Dredged Material and Guidelines for Future Research (Draft Version), U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

Kinsman, Blair, 1965, Wind Waves, Prentice-Hall, N.J.

Klein, W.H., 1957, Principal Tracks and Mean Frequencies of Cyclones and Anticyclones in the Northern Hemisphere, Research Paper No. 40, U.S. Weather Bureau, Dept. of Commerce, Washington, D.C.

Koh, Robert C.Y., and Y.C. Chang, 1973, Mathematical Model for Barged Ocean Disposal of Wastes, U.S. Environmental Protection Agency, Office of Research and Development, Washington, D.C., December, 1973.

Krishnappan, B. G., 1975, Dispersion of Granular Material Dumped in Deep Water, Scientific Series No. 55, Inland Waters Directorate, Canada Centre for Inland Waters, Burlington, Ontario.

Lake Survey Center, 1975, personal communication with the Detroit office regarding precipitation data for the Lake Superior Basin, October 20, 1975.

McCulloch, J.A.W., and V.S. Derco, 1968, The Great Lakes Wind-Wave Study Report No. 1, Technical Memoranda, Canada Department of Transport, Meteorological Branch.

Mortimer, C.H., and E.J. Fee, 1972, Free Surface Oscillations and Tides of Lakes Michigan and Superior, Contribution No. 99, Center for Great Lakes Studies, University of Wisconsin, Milwaukee.

Phillips, D.W., and J.A.W. McCulloch, 1972, The Climate of the Great Lakes Basin, Climatological Studies Number 20, Atmospheric Environment Service, Toronto.

Ploeg, J., 1971, Wave Climate Study - Great Lakes and Gulf of St. Lawrence, Volume 1, Mechanical Engineering Report MH 107A, Division of Mechanical Engineering, National Research Council of Canada, Ottawa.

Ragotzkie, Robert A., 1966, The Keweenaw Current, A Regular Feature of Summer Circulation of Lake Superior, Univ. of Wisc. Dept. of Meteorology, Tech. Report 29.

_____, 1974, Vertical Motions Along the North Shore of Lake Superior, Proc. 17th Conf. Great Lakes Research, International Assoc. Great Lakes Research, p. 456-461.

_____, and H.J. Niebauer, 1975, Temperature Regime in Lake Superior At Silver Bay, Minnesota, Verh. Internat. Verein, Limnol., Stuttgart, Germany.

Reitan, Clayton H., 1974, Frequencies of Cyclones & Cyclogenesis for North America, 1951-1970, Monthly Weather Review, American Meteorology Society, December, 1974.

Richards, T.L., and J.G. Irbe, 1969, Estimates of Monthly Evaporation Losses from the Great Lakes 1950 to 1968 based on the Mass Transfer Technique, Proc. Twelfth Conf. Great Lakes Res. Internat. Assoc. Great Lakes Res., 469-489.

_____, and D.W. Phillips, 1970, Synthesized Winds and Wave Heights for the Great Lakes, Climatological Studies Number 17, 1970.

Smith, Ned P., 1972, Summertime Temperature and Current Characteristics of Central Lake Superior, PhD. thesis, Univ. of Wisconsin, Madison, Wisc.

Sydor, Michael, 1974, Current Patterns and Turbidity in Extreme Western Lake Superior Summer 1973, University of Minnesota-Duluth, Lake Superior Basin Studies Center, Sept. 15, 1974, Report to the St. Paul District Office, U.S. Army Corps of Engineers U.S.A.C.E. contract DACW 37-74-C-0014.

_____, 1975, Preliminary Evaluation of Red Clay Turbidity Sources for Western Lake Superior, Lake Superior Basin Studies Center, Univ. of Minn.-Duluth, Feb. 6, 1975, Report to the St. Paul District Office, U.S. Army Corps of Engineers, U.S.A.C.E. Contract DACW 37-74-C-0014.

U.S. Department of Commerce, 1963, Summary of Hourly Observations-Duluth, Minnesota: 1951-1960, Decennial Census of United States Climate, Climatography of the United States No. 82-21.

Yeske, Lanny Alan, 1973, The Structure of the Keweenaw Current by Photogrammetry, PhD. thesis, University of Wisconsin.